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Costs and energy efficiency of long-distance hydrogen transport options

Master Thesis

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Abstract - German

Grüner Wasserstoff gilt als einer der wichtigsten zukünftigen erneuerbaren Energieträger. Eine effiziente und kostengünstige Ausgestaltung der Übertragungs- und Lieferinfrastruktur ist entscheidend, um eine Wasserstoffwirtschaft zu ermöglichen. Die kosteneffizientesten Pfade für den Landtransport von Wasserstoff wurden bereits in mehreren Studien untersucht. Der Schiffstransport ist jedoch maßgeblich für potenzielle globale Wasserstofftransportketten und erfordert weitere Forschung. Transportmodelle benötigen zudem eine Vielzahl von Daten, um Unsicherheiten zu berücksichtigen und robuste Schätzungen zu liefern. Diese Masterarbeit analysiert die Kosten, die Energieeffizienz und die Umwandlungs- und Transportenergie möglicher Wasserstofftransportoptionen. Sie umfasst den LKW-, Pipeline- und Schiffstransport und die Wasserstoffspeichermedien komprimierter Wasserstoff, Flüssigwasserstoff, Ammoniak und liquid organic hydrogen carriers. Es wurde ein Lieferkettenmodell auf Basis einer umfassenden techno-ökonomischen Analyse in der Programmiersprache R erstellt und mit Daten aus der wissenschaftlichen Literatur und Experteninterviews bestückt, um die Wirtschaftlichkeit und Energieeffizienz von Wasserstofftransportpfaden zu untersuchen.
Die Ergebnisse zeigen, dass die Transportkosten stark von den erforderlichen Umwandlungen und von der Transportdistanz abhängen. Bei einem 500 km Pipelinetransport belaufen sich die Transportkosten auf 0,64 €/kgH2 und 10,1% der transportierten Energie werden in Umwandlung und Transport investiert. Ein 500 km Überseetransport mit Flüssigwasserstoff-Tankern kostet 1,75 €/kgH2 und erfordert 22,7% der transportierten Energie. Für den Landtransport sind Wasserstoff-Pipelines die kosteneffizienteste Option. Wenn eine Kombination aus Land- und Schifftransport erforderlich ist, ist gemäß dieser Analyse eine Kombination aus Flüssigwasserstoff-Tankschiffen mit Flüssigwasserstoff-LKWs oder Pipelines die kostengünstigste und energieeffizienteste Lösung.

Schlagworte: Erneuerbare Energieträger, Wasserstoff, Ferntransport, Energieeffizienz, Wasserstofftanker, Wasserstoffpipeline, Wasserstoff-LKW, liquid organic hydrogen carrier, verdichteter Wasserstoff, Ammoniak, Lieferkettenmodell

Abstract - English

Green hydrogen is considered as one of the key future renewable energy carriers. An efficient and cost-effective design of the transmission and delivery infrastructure is crucial for its application. Several studies have investigated the most cost-efficient pathways for hydrogen land transport. However, ship transport is crucial for potential global hydrogen supply chains and further research is necessary. Furthermore, transport models require a variety of input parameters to account for uncertainties in the input data and provide robust estimates. This master thesis analyses the costs, energy efficiency and conversion and transport energy of possible hydrogen transport options. It includes truck, pipeline and ship transport of the hydrogen storage mediums compressed hydrogen, liquid hydrogen, ammonia and liquid organic hydrogen carriers.

For that purpose, a techno-economic supply chain model based on a comprehensive techno-economic analysis was built in the statistical programming language R and populated with data from scientific literature and expert interviews.

The results show that the transport costs are highly dependent on the required conversions and on the transport distance. At 500 km transport distance the transport via pipeline costs 0.64 €/kgH2 and 10.1% of transported energy have to be invested for conversions and transport. A 500 km transport overseas with liquid hydrogen tankers costs 1.75 €/kgH2 and requires 22.7% of energy in total. For land transport, hydrogen pipelines are the most cost-efficient option. If a combination of land and overseas transport is needed, a combination of liquid hydrogen tankers with liquid hydrogen trucks or pipelines is suggested as the most cost-efficient and most energy-efficient solution according to our results.

Keywords: renewable energy carriers, hydrogen, long-distance transport, energy efficiency, hydrogen carriers, hydrogen pipeline, hydrogen truck, liquid organic hydrogen carrier, compressed hydrogen, ammonia, supply-chain model

Contents

List of Abbreviations

Calculations

$\dot{W}^t_{\Delta S->0}$	Adiabatic Work	$\frac{kWh}{kg}$
$\dot{Q}_{mass}$	Mass flow rate	$\frac{kg}{s}$
γ	Specific heat ratio of hydrogen	1.41
ρ	Mass density	$\frac{kg}{m^3}$
C_{an}	Average yearly cost of equipment	€ 2015
C_{kg}	Costs per kg of hydrogen	€2015/kg
N_{rt}	Maximal Number of round trips in one year	
P_{in}	Pressure at the start of a process	bar
P_{out}	Pressure at the end of a process	bar
sf	scaling factor	
v	Fluid velocity	$\frac{m}{s}$
a	years	
C_MWh	Costs per MWh of hydrogen based on LHV	€2015/MWh
Capacity	Deliverable amount of hydrogen; deliverable payload; net capacity	kg, t, t/d
CRF	Capital Recovery Factor	
d	Diameter of the pipe	mm
dwt	Deadweight tons	t
FinCost60	final cost of hydrogen incl. generation, transport, generation, loss at 70€	€2015/MWhH2
GCapacity	gross capacity; deliverable amount of medium	kg, t, t/d
gt	Gross tonnage, non-dimensional parameter for ship sizes	
HFO	Heavy Fuel Oil	
i	Interest rate	
L	Distance	km
LHV	Low Heating Value	
LT	Load Time	h
MWh	mega watthour	

N	Number; number of compression steps	
Q	Quantity of hydrogen transported/handled in one year	kg
t	number of years; lifetime of technical equipment; depreciation period	
TF	Total amount of Fuel input invested transport step	l; kWh
TFC	Total Fuel Costs	€ 2015
TI	Total amount of input invested in one transport or conversion step	
TIC	Total Input Costs in a conversion step other than the medium	€ 2015
TLC	Total Labor Costs	€ 2015
TOMC	Total Operations and Maintenance Costs	€ 2015
triptime	time required for one round trip	h
ULT	Unload Time	h

Overall

ADR	European Agreement concerning the International Carriage of Dangerous Goods by Road	
ASU	Air Separation Unit	
CAPEX	Capital Expenditures	€ 2015
CG	Compressed Hydrogen Gas	
CH4	Methane	
ConvE	Conversion Energy	$\frac{MWh}{MWh_{H2}}$
ConvTransE	Conversion and Transport Energy	$\frac{MWh}{MWh_{H2}}$
DBT	Dibenzyltoluene	
EE	Energy Efficiency	kWh/kg
GGVSEB	Gefahrgutverordnung Straße, Eisenbahn und Binnenschifffahrt	
HB	Haber-Bosch synthesis loop	
IEA	International Energy Agency	
LIQ	Liquid Hydrogen	
LNG	Liquid Natural Gas	
LOHC	Liquid Organic Hydrogen Carrier	

LPG	Liquefied petroleum gas	
NH3	Ammonia	
OPEX	Operational Expenditures	€ 2015
pipe	Referring to transport via pipeline	
PSA	Pressure Swing Adsorption	
ship	Referring to ship transport	
train	Referring to transport by rail	
TransE	Transport Energy	$\frac{MWh}{MWh_{H2}}$
truck	Referring to truck transport	

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1 Introduction

An efficient and cost-effective design of the transmission and delivery infrastructure is crucial for the application of hydrogen as an energy carrier. Hydrogen is one potential energy carrier for renewable energy systems and can be an important option for the decarbonisation of the energy sector and industries, for example as energy carrier in the mobility sector [70, 77] or as a reductant in steel making [11]. On the one hand a high level of penetration of renewable hydrogen in these sectors could potentially lead to a more local energy supply. On the other hand, it has also been argued that global trade and thus transport and delivery of renewable fuels such as hydrogen could persist or even increase due to, among others, differing production conditions such as land availability and social acceptance [73]. The physical and chemical properties of hydrogen such as high volatility and low volumetric energy density [97] pose challenges to the technological solutions suitable for high-volume, long-distance transport. The high volatility complicates long-term storage and increases material requirements. Due to its low volumetric energy density hydrogen has to be converted into another medium before transport to ensure an economic energy throughput. Several media and modes of transport i.e., technological pathways have been suggested to tackle these challenges. Major differences across the pathways arise from transportation costs of hydrogen, the energy efficiency of conversion, losses and from the energy demand for conversion into and out of media and for transport. This thesis will thus compare the most promising technological pathways for the long-distance transport of hydrogen to identify the most cost-efficient pathway. The research questions are:

1. What are the energy efficiencies that result from each pathway?
2. What are the costs that arise from each pathway?
3. Which of the pathways are most efficient in terms of costs and conversion and transport energy?
4. What critical parameters have the highest influence on overall costs of the pathways?

2 Literature Overview

There is a considerable amount of scientific work concerned with the transport of hydrogen, most of it published in the last ten years.

Studies differ greatly in terms of examined technologies and the selection of supply chain elements included (e.g. generation, electrolysis, several modes and media of transport, distribution among others). Some focus on environmental assessment and/or life cycle assessments of hydrogen transportation, whereas others concentrate on cost estimates or combine both.

In 1998 the National Renewable Energy Laboratory published a detailed report on the costs of hydrogen transport [7]. The report compares pipelines, trucks and rail transport as well as the transport of the media gas, liquid and metal hydrides. It shows that pipelines are the cheapest mode for the transportation of large quantities of hydrogen. This report set up a methodological basis for cost estimations of hydrogen transportation in this thesis.

Recent studies with the highest similarity regarding the aim of this thesis were carried out by Lahnaoui, Wulf, and Dalmazzone, Lahnaoui et al. and Reuß et al. [43, 44, 67, 68], although the scope of transport technologies is narrow. Lahnaoui, Wulf, and Dalmazzone [43] perform a cost optimization for the transport of hydrogen in various physical states. They focus on different forms of truck transport and include distribution, performing a node-to-node mixed-integer linear optimization. A subsequent paper [44] assesses the usage of hydrogen in the mobility sector. They showed that the cost-optimal solution to long distance and large capacity transport is using compressed gas trucks at 540 bar that can withstand stronger compression. Reuß et al. [67] considers pipelines (for gaseous hydrogen) and trucks as well as trucks for liquid organic hydrogen carriers (LOHC). They find that LOHC becomes relevant as transport media if large storage is included and that liquid hydrogen trucks only become an option for distances over 500 km.

Ajanovic analyses a complete hydrogen supply chain for hydrogen application in Austria. The transport covers the modes pipeline, truck and ship and liquid and compressed gas media. The study focuses on deriving long-term scenarios of hydrogen penetration, the results therefore center around predictions of when certain stages of economic penetration will be reached [see also 3]. Ajanovic concludes that transport in a liquid state is cheaper than gaseous transport for trucks and ships but pipelines become the cheapest option if large quantities are being transported.

Yang and Ogden [98] conducted a similar yet broader study with trucks and pipelines. For large capacities it concludes that pipelines are the preferable option, with capital costs being the most influential variable. The same is true for Demir and Dincer [21] who additionally study the environmental impact of the pathways.

Murthy Konda, Shah, and Brandon [57], Samsatli, Staffell, and Samsatli [72, 71] and Almansoori and Shah [6] present hydrogen networks for Great Britain and the Netherlands, optimized for application in the heat and mobility sector with a focus on distribution and infrastructure design.

The International Energy Agency (IEA) published an extensive report on hydrogen production, transmission and usage called "The Future of Hydrogen. Seizing today's opportunities" [85] in June 2019. To evaluate transmission options the IEA include the media liquid hydrogen, gaseous compressed hydrogen, ammonia and LOHC (LOHC being methylcyclohexane (MCH)), modes of transport include truck, ship and pipeline.

Apart from these overarching studies that compare different transport pathways and include several media and modes, there are also studies that are only concerned with one medium and/or mode. They are essential for the understanding of the subsystems.

For hydrogen transmission pipelines those studies are: André et al., [9, 8], Baufumé et al. [15] and Parker [61]. Shipping costs and assumptions can be derived from Balat [12], Fasihi, Bogdanov, and Breyer [28, 29] and Kamiya, Nishimura, and Harada [42]. Apart from the already discussed sources that consider truck transport, Reddi et al. [66] provide detailed information (including costs) of different hydrogen truck forms. There are also numerous studies that focused on the medium. LOHC and ammonia are analyzed by Aziz, Oda, and Kashiwagi [10], Obara [60], Teichmann et al. [84], Wijayanta et al. [93] and Ikäheimo et al. [37]. Liquefaction and different pressure levels of gaseous states appear in the already presented sources.

This thesis is set apart from the aforementioned studies in three main ways. Firstly, the range of media is broad, as four media, four trucks, three ships and one pipeline are part of the pathways considered. Especially the inclusion and comparison of ships is rare and to the author's knowledge has only been reported in a comparable way in the IEA's report "The Future of Hydrogen" [85]. Secondly, this thesis takes into account costs, energy efficiency and conversion and transport energy for the assessment of pathways. Thirdly and most importantly, this thesis allows for a range of values per input parameter. All of the overarching studies presented only take one value per crucial parameter, for example only one capital expenditure (CAPEX) estimation. This approach masks the uncertainties in the assessments - uncertainties, which are substantial as confirmed by the significant variation in input parameters found in different studies.

3 Data and Methods

In the following, a brief terminology is given for the meaning of *mode, medium* and *pathway*.

- Mode: The type of transport technology, for example truck, pipeline or ship.
- Medium: The state of hydrogen during transportation, e.g. gaseous, liquid or in a LOHC. A mode of transport can be used for different media and vice versa.
- Pathway: A chain consisting of all technological processes applied to hydrogen from the place of origin to the place of use. A pathway can include a combination of different modes of transport and media and includes the conversions between different media.

This thesis considers only the long-distance transport of hydrogen, explicitly excluding hydrogen generation, the end use and also storage. This implies that every pathway starts with pure gaseous hydrogen and ends with pure gaseous hydrogen. Figure 1 shows a schematic overview of the pathways in this thesis. The blue squares represent the media, which are gaseous hydrogen, liquid hydrogen, LOHC and ammonia. The icons inside the squares represent the modes of transport considered in this thesis. The conversion steps are depicted in the black squares left and right of the medium. The braces around the technologies symbolize that also a combination of medium and mode of transport are possible to form one pathway, e.g. first transport ammonia by ship and then use a pipeline for the transport of gaseous hydrogen.

3.1 Methods

Here, we first present the results of a review literature that we used to identify the most suitable technologies for the transport of large quantities of hydrogen. The selected media and modes of transport that are shown in figure 1 are discussed in chapter 4, which focuses on overall technological and physical aspects and the identification of the parameters that are essential

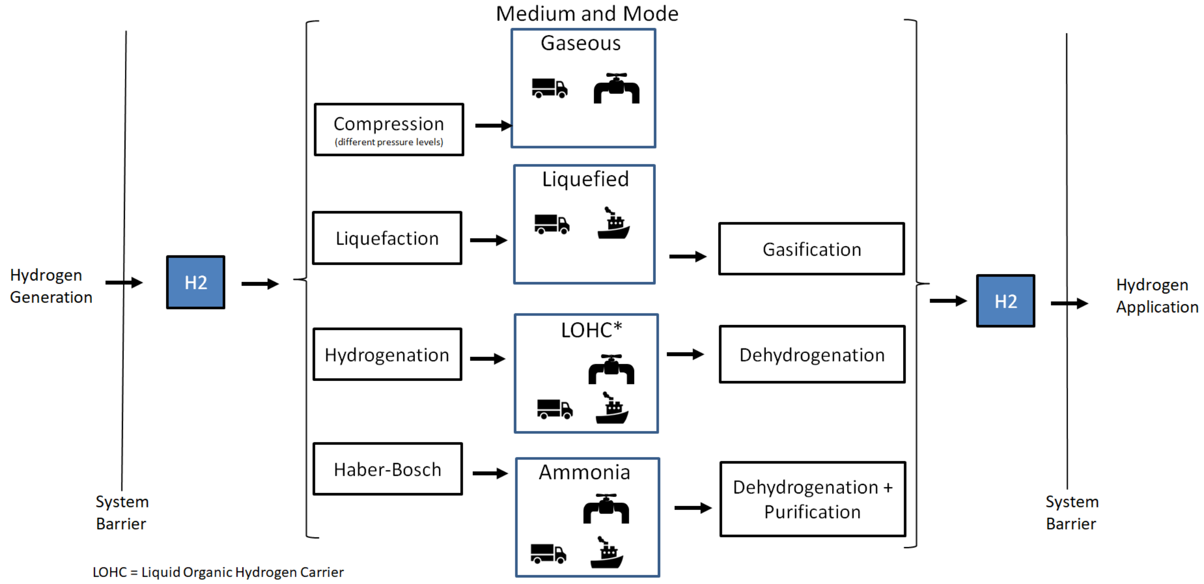


Figure 1: Hydrogen transportation pathways

for the calculation of conversion and transport costs. The parameters are collected from scientific literature, industry reports, technological data sheets and telephone interviews. The input data sheets are available in the repository. The parameters are summarized per mode and medium in the respective sections of chapter 4. We harmonized the input parameters in terms of units of measurement, currency and inflation as outlined in chapter 3.2.
The model was implemented in the statistical programming language R [64] using RStudio and the R-packages tidyverse [92] and ggplot2 [91]. Data and R scripts used in this thesis are available for reference in the repository in GitHub[1] under the MIT license. The model was implemented according to the technologies and the equations shown in chapter 4. Every mode and conversion is calculated separately. Input parameters such as the interest rate, electricity cost or transport distance that are relevant for more than one of technologies are set as a range, see chapter 3.3.1. The model loops over all input parameters, so that every possible combination of parameters is included in the results. The model returns one output table per conversion or mode of transport, representing one combination of parameters (one scenario). The output tables include the input parameters and the results per scenario, which are the loss of hydrogen in %, conversion and transport energy (ConvTransE) in MWh per MWh of transported hydrogen and the costs per MWh of transported hydrogen C_MWh. ConvTransE is important to consider, as it should be significantly lower than 1, as a factor of 1 would mean that more than 1 MWh are invested in the transport and conversion of 1 MWh of hydrogen.

The output tables are subsequently merged into pathways using the join functions provided by the tidyverse package and for big joins the join functionalities of the data.table package [22]. Firstly, the conversions to different media are joined into all conversions necessary for one pathway. Then these joined conversion tables are joined with the output tables for the respective

[1] https://github.com/ZalpZilp/Masterthesis_Hydrogen

transport technologies to form the pathways result tables. In some cases the joins result in tables with more than 100,000,000 rows. To reduce computation time in the susequent analysis, a subset of 400,000 rows is randomly selected from the bigger result tables. The results are plotted with ggplot2.

To get a better understanding of the overall costs of hydrogen at the point of delivery, the measure final costs (FinCost) is introduced. These final costs include an hydrogen generation price, costs for conversion and transport and the loss of hydrogen during transport and conversions. The hydrogen generation price ($H2_{price}$) is set to 30, 50, 60 and 80 €/MWh based on the analysis of baseload electricity hydrogen supply by Fasihi and Breyer [30].

$$FinCost = \frac{H2_{price}}{1 - loss} + C_{MWh} \tag{1}$$

Finally, the most competitive modes and mediums for land and sea transport based on FinCost are selected. These pathways are merged into combined pathways that include one type of sea transport, one type of land transport and the necessary conversions. To make the computation possible, a subset of 10,000 rows is randomly sampled from the single pathway result tables before the merge. The resulting combined pathway tables have once more over 10,000,00 rows, so that again a subset of 400,000 rows is randomly sampled.

To answer the fourth research question that assesses the influence of parameters on C_MWh, a multiple linear regression with standardized coefficients is performed. The dependent variable C_MWh is explained by all input parameters that are not constants, the regressions is performed for every output table separately. The regression is possible as according to Wooldridge asymptotic normality can be assumed due to the large sample size which means that the ordinary least squared estimators are approximately normally distributed [95, p. 174]. Using standardized coefficients instead of normal coefficients is useful, as the independent variables have units of measurement that are otherwise not comparable. The z-score standardization is performed for the dependent and the independent variables, it subtracts the mean from of every variable and divides by its standard deviation: $z_i = \frac{x_{i1} - \overline{x_i}}{\widehat{\sigma_1}}$ [95, p.187ff]. Then the regression is performed. The standardized coefficients are now interpretable as "one standard deviation change in this independent variable results in x standard deviation change in the dependent variable".

3.2 Data harmonization

For the selection of conversion and transport technologies, a broad range of technologies is considered. Furthermore, the data collection spans over publications from the last 20 years. To keep technologies and parameters comparable, some assumptions have to be made. Firstly, for every conversion step or every part of a conversion step only the most economic technology is selected, even though competing technologies may be available. For example the tubes of compressed hydrogen trucks can be made of steel or composite. As composite tube trailers are more cost-efficient, only this tube type features in the analysis. Therefore, all parameters that have a range still refer to the same technology, e.g. the specifications on capacity of compressed hydrogen trailers may still have a range but all relate to composite tube trailers. Furthermore, the data has to be harmonized for currency, inflation and units of measurement. The methods used in this harmonization and the basic equations used for the model setup are laid out in the following.

3.2.1 Equivalent annual costs

This study faces the challenge to compare transportation pathways that use very different equipment and plants, from whole specialized hydrogen ships to small compressors. In order to compare CAPEX over the individual lifetime of each equipment, the Equivalent Annual Cost Method is used [9, 43, 44, 83, 23]. Using an interest rate i and a lifetime t it calculates the CAPEX per year:

$$C_{an} = \frac{CAPEX}{\sum_{t=1}^{n}(\frac{1}{(1+i)^t})} + OPEX = \frac{CAPEX}{(\frac{1-(1+i)^{-n}}{i})} + OPEX = CAPEX \cdot CRF + OPEX \tag{2}$$

The Factor $\frac{1-(1+i)^{-n}}{i}$ is known as the Capital Recovery Factor (CRF); the CRF is defined as $\sum_{t=1}^{n} \frac{1}{(1+i)^t} = \frac{1-(1+i)^{-n}}{i} = \frac{1}{CRF}$.

This method also implies that OPEX costs have to be calculated per year as the defining unit of measurement is costs per year C_{an}. This is relevant for OPEX cost components that vary per number of trips per year (e.g. for trucks or ship trips) as the number of trips carried out in one year have to be defined. This study assumes a transport scenario of large quantities over large distances, therefore a steady ”flow” of hydrogen is postulated so that all modes take the maximum number of trips. Therefore the cost reference is the annual throughput of hydrogen or annual transported quantity (Q) of hydrogen [compare 36]. In order to keep the hydrogen flow realistic (e.g. limited amount driving during night or weekends), the number of trips or the load factor is reduced by an availability factor in percent if necessary based on literature values.

3.2.2 Currency and inflation

All prices are given in 2015 €. Prices from former or more recent years are adjusted using the Harmonised Consumer Price Index (HCPI) published by Eurostat [26] with the base year 2015. If sources give prices in US dollar $ or other currencies they are converted using the historic currency conversion rates published by Eurostat [25].

3.3 Key equations

Key equations feature in the calculation for all modes and conversions. If the calculations deviate or additional equations have to be added, the exact calculation is presented in the corresponding chapter. All calculations can be reviewed in the repository.

Investments that can be scaled according to the quantity processed within a certain time frame are scaled according to this equation:

$$CAPEX = BaseCost \cdot (\frac{Q}{BaseQ})^{sf} \tag{3}$$

Where $BaseCost$ is the investment cost of a facility with the capacity $BaseQ$ that is scaled to the actual quantity Q needed in the model using the scaling factor sf (usually between 0.6 and 0.66).

Annual TOMC (Total Operations and Maintenance Costs) are given as a function of CAPEX, such as:

$$TOMC = x \cdot CAPEX \tag{4}$$

with x typically being in the interval [0.02,0.5]. In OPEX all variable costs over one year are assimilated, those are for example Total Fuel Costs (TFC, depend on Q), Total Labor Costs (TLC), Total Input Costs such as electricity (TIC, also depend on Q) and TOMC.

$$OPEX = TFC + TLC + TIC + TOMC \tag{5}$$

Annual Costs per MWh of hydrogen C_MWh are the total costs per MWh of hydrogen calculated as an average over one year that arise from the transport or conversion step. The lower heating value (LHV) of hydrogen is approximated to 33.33 kWh/kg for conversions between the amount of hydrogen in kg and MWh.

$$C_{kg} = \frac{C_{an}}{Q} = \frac{CAPEX \cdot CRF + OPEX}{Q} \qquad C_{kWh} = \frac{C_{an} \cdot 33.33\frac{kWh}{kg}}{Q} \tag{6}$$

In some cases, a certain percentage of Q (quantity of hydrogen processed/transported per year) is lost during the transport or conversion. In this case, the cost calculations are performed with the initial Q, as this is the defining factor for the dimension of the facility. C_{kg} on the other hand is calculated using $Q2$ if $Q2 \neq Q$, meaning the quantity of hydrogen that actually results at the end of a process step/pathway; $Q2 = (1 - loss) \cdot Q$.

ConvTransE is calculated as relevant amounts of energy invested into a transport or conversion step (in the form of electricity, natural gas, gasoline and heavy fuel oil) per kg of hydrogen. It is then converted into $MWh_{ConvTransE}$ per $MWh_{hydrogen}$ using the LHV of 33.33 kWh/kg.

$$ConvTransE = (\frac{TF + TI}{Q}) \tag{7}$$

3.3.1 Predefined variables and constants

For the input parameters distance, interest rate, cost of diesel, cost of heavy fuel cost, electricity cost, natural gas cost, quantity of hydrogen Q and diameter of the pipeline values are not directly taken from literature for each individual conversion or transport step but predefined for all calculations. Their range reflects the values found in literature but is typically broader. This make the output tables comparable on the level of these input parameters, avoids unnecessary variance in the output tables and makes it possible to join the output tables over these parameters. Furthermore, some constants had to be defined for the model, such as the LHV of hydrogen. They are listed in table 1.

Table 1: Data summary for predefined variables

parameter	**values**	**unit**	**source/ explanation**
H2 generation price	30/50/60/80	euro/MWh	based on [29]
diameter of pipeline	from 100 to 300 by 20	mm	-
distance (L)	10/50/100/500/1000/5000	km	distance on land
distance (L_w)	100/200/500/1000/5000/10000	km	distance on sea
interest rate	0.01/0.05/0.1/0.15	-	-
diesel cost	0.5/1/1.5/2	euro/liter	-
heavy fuel oil cost	350/400/500/550	euro/ton	-
electricity	0.06/0.08/0.1	euro/kWh	NULL
natural gas cost	0.015/0.018/0.02/0.023	euro/kWh	-
Quantity of hydrogen Q	365/1000/5000/10000/100000/180000	tons/year	-
generic scaling factor sf	0.66	-	fall back sf
LHV hydrogen	33.33	kWh/kg	[87]
LHV methane	13.902778	kWh/kg	[87]

4 Technology data

The selection of the technologies that are included in the model is not completely straightforward, as in theory a lot of technologies are available or are being developed. The selection was done based on the available studies at the moment and following the principles outlined in chapter 3.2. This chapter thus outlines the reasoning behind every technology, explains the technology, gives the equations used to model it and provides an overview over the relevant input parameters. The chapter starts with the mediums compressed hydrogen gas, liquid hydrogen, LOHC and ammonia and outlines the necessary conversion steps. Then the modes of transport trucks, pipelines and ships are addressed.

4.1 Compression

Gaseous hydrogen needs to be compressed to varying pressure levels accordings to the mode: 500 bar for truck transport and 100 bar for pipeline. Therefore, large industrial compressors are part of the gaseous hydrogen pathways. Compressors are modelled after Lahnaoui et al. [45]. The calculations are similar to Drennen and Rosthal [23] and Amos [7]. A multiple stage compressor ($N = 5$ stages) is assumed. Firstly, the adiabatic work in kWh/kg of the compression itself $\dot{W}^t_{\Delta S->0}$ is calculated [compare 68, 9, 33, 19]:

$$\dot{W}^t_{\Delta S->0} = (\frac{\frac{Z \cdot T \cdot R}{M}}{3600s} \cdot N \cdot \frac{\gamma}{\gamma - 1} \cdot [(\frac{P_{out}}{P_{in}})^{\frac{\gamma-1}{N \cdot \gamma}} - 1]) \cdot f_{\eta_1,\eta_2} \tag{8}$$

With the hydrogen compressibility factor Z approximated to 1, the temperature T approximated to 293.15 K, the universal constant of ideal gas $R = 8.314 JK^{-1}mol^{-1}$, the molar mass of hydrogen $M = 2.15$, $N = 5$, the specific heat ratio of hydrogen $\gamma = 1.41$ and the pressure levels P_{out} and P_{in} in bar, $\dot{W}^t_{\Delta S->0}$ has to be reduced by two efficiency factors: the first efficiency factor at 90% is the efficiency of the electrical motor that powers the compressor $\eta_1 = 0.9$. The second gives the adiabatic efficiency of the compression itself which is assumed to be $\eta_2 = 0.75$ [98]. Compressing one kg of hydrogen from atmospheric pressure to 500 bar therefore requires roughly 3.36 kWh.

The cost calculations follow the basic structure outlined in chapter 3.3, except for the CAPEX calculations, that use the the two scaling factors $sf_{power} = 0.8$ and $sf_{pressure} = 0.18$ to adjust for varying power and pressure levels.

$$CAPEX_{comp} = BaseCost \cdot BasePower \cdot (\frac{\dot{W}^t_{\Delta S->0} \cdot Q}{\eta_1 \cdot BasePower \cdot \cdot 8760h})^{sf_{power}} \cdot (\frac{P_{out}}{BasePressure})^{sf_{pressure}} \tag{9}$$

All other defining parameters (except BaseCost and BasePower) are summarized in table 2, for sources please refer to repository.

Table 2: Data summary for the compressor (only compressors $\geq 10kW$)

Technology	**Factor**	**Unit**	**mean**	**min**	**max**
Compressor	Compressor_TOMC	% of CAPEX	5.25	3	10
Compressor	Compressor_t	years	15	15	15
Compressor	Compressor_Loss	%	0.5	0.5	0.5

No decompression station is needed, as a simple valve is sufficient for the outlet of the gas.

4.2 Liquid hydrogen

One option for increasing the volumetric energy content is liquefying the hydrogen. This increases the volumetric energy content by 787% from appr. 0.01 MJ/l to appr. 8.5 MJ/l[1]. The boiling point of hydrogen lies at 21,15 K. The hydrogen has to be brought under that temperature and kept under it constantly so that it stays liquid. Boil-off occurs, if a fraction of the liquid gas re-enters the gaseous state. Often boil-off results in consistent losses.

4.2.1 Liquefaction

There are two main cost components for the liquefaction of hydrogen: the energy requirements for the liquefaction process and the investment costs for the liquefaction plant. Estimations on energy requirements for the whole plant are consistent throughout the literature, they lie between 5.9 and 6.78 kWh/kg [85, 67, 68, 96, 80, 43, 18]. These estimations are optimistic and assume technological improvements, current liquefaction plants already in operation often have an energy requirement of up to 13 kWh/kg [58, 19]. The second lowest assumption for the energy requirement for liquefaction of 6.1 kWh/kg or 0.183 kWh/kgH_2 stems from the IEA [85].

Cost assumptions for liquefaction plants on the other hand vary significantly. The biggest plant size assumption is again done by the IEA at 712 tons/d [85]. This is contrary to the Nexant Report which concludes:

> *Allowable plant sizes should be restricted to values in the range of 0 to 200 metric tons per day. For liquefaction requirements greater than 200 metric tons per day, multiple trains should be used. [58, p.2.64]*

Cardella, Decker, and Klein propose a capacity of 100 tons/d [18] for scenarios with high hydrogen demand. Their analysis demonstrates that employing a 100 tons/day plant instead of a 5 tons/day plant reduces the specific costs by 67%. Reuß et al. [67] state that the estimated investment costs have increased over the last decades with cost assumptions becoming higher and more realistic.

The cost calculations follow the basic structure outlined in chapter 3.3, the main cost components (except BaseCost) are summarized in table 3.

4.2.2 Evaporation

When the liquid hydrogen arrives at its destination it has to be gasified for further uses. This process is either called evaporation, regasification, gasification or vaporization. A lot of sources [1, 7, 18, 19, 43, 80] that include liquefaction/liquid hydrogen transport in their analysis omit evaporation plants completely. In theory, evaporation occurs 'naturally' due to heat exchange with the ambient air if the liquid hydrogen is stored in tanks without insulation. This process is not desirable for large quantities of hydrogen though and implies the complete loss of the cryogenic energy.

Wijayanta et al. acknowledge that “in general, liquid H2 requires regasification (re-evaporation) before being utilized” [93, p. 6] and Trevisani et al. affirm: “At the end of the storage and transport chain, gasification is always necessary for final use”[86, p. 147]. Current terminals for liquefied natural gas (LNG) also deploy evaporation plants. Hence, they are included as necessary last step in the liquid pathways in this study.

The cost components of evaporators are similar to those of the liquefaction plant as they mainly include the investment cost and the energy requirement. In the Nexant report the authors note that due “to the wide variation in geographic and climatic conditions in which terminal vaporizers may be located, it is difficult to estimate the cost of natural gas consumption required to heat the heat exchanger tubes” [58, p. 67]. Therefore, energy requirements can only be approximated. For this analysis, a range between 0.37 and 0.6 kW(el)/kg(H2) is assumed according to Reuß et al. [67, 68].

The cost calculations follow the basic structure outlined in chapter 3.3, the main cost components (except BaseCost) are summarized in table 3. There are no relevant losses that occur during the evaporation process.

Table 3: Data summary for the liquefaction and evaporation plant

Technology	**Factor**	**Unit**	**mean**	**min**	**max**
Liquefier	Liquefier_TOMC	% of CAPEX	4.7	3.5	8
Liquefier	Liquefier_t	years	22.5	20	30
Liquefier	Liquefier_ElectricityUse	kWh/kgH2	7.34	5.9	11
Liquefier	Liquefier_Loss	%	1.64	1.62	1.65
Evaporator	Evaporator_TOMC	% of CAPEX	3	3	3
Evaporator	Evaporator_t	years	10	10	10
Evaporator	Evaporator_ElectricityUse	kWh/kgH2	0.48	0.37	0.6

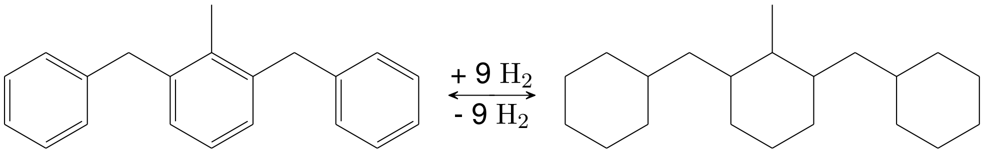
4.3 LOHC

Liquid Organic Hydrogen Carriers (LOHC) is a loose collective term for “flexible media for the storage and transportation of renewable energy [...][which are] reversibly hydrogenated and dehydrogenated using catalysts at elevated temperatures” [1, p. 803]. In theory, a wide array of chemical compounds that bind hydrogen could be used as LOHC. There are several cyclic hydrocarbons and heterocyclic compounds under consideration, such as the pairs benzene/cyclohexane, toluene/methylcyclohexane and N-ethylcarbazole. In order to be applied on an industrial scale for hydrogen storage and transport, the compound has to fulfill a wide array of criteria, such as non-toxicity, commercial availability or hydrogen storage capacity. The hydrocarbon that seems to have won the race for an application in energy transport and energy storage is dibenzyltoluene (H0-DBT)/ perhydro-dibenzyltoluene (H18-DBT) [96, 69, 27, 1, 67, 68, 17, 93, 59, 38, 63]. N-ethylcarbazole appears to be optimal for applications in the mobility sector involving fuel cells [59]. DBT has “reasonable gravimetric and volumetric hydrogen storage capacities” [1, p. 820], is liquid at normal temperatures and pressure levels, thermally robust, safe to handle and use, relatively cheap and already applied on a larger scale as a heat transfer fluid [67, 1, 17]. Furthermore, DBT is already commercially applied as a LOHC in Germany and Japan [59, 1]. Therefore, the term LOHC refers to the H0-DBT/H18-DBT pair in this analysis, though this specification is less relevant, as most cyclic compounds share overall similar characteristics. Thus, some assumptions for other non-dibenzyltoluene LOHCs can be used for dibenzyltoluene, especially those for transport and storage options.

According to Brückner et al. and Eypasch et al. [17, 27] the process is as follows: A LOHC-based pathway starts with the hydrogenation of DBT, in which H0-DBT reacts with hydrogen in an exothermal reaction that releases $\sim 65kJ/mol$ which is $\sim 223kJ/kg$ in the form of heat. The double bonds in the carbocycles open so that $1H_2$ per double bond can bind to the molecule, this process is depicted in figure 2. The reaction is catalyzed by a commercial Ru on aluminum catalyst and the DBT is fully hydrogenated. If simultaneous heat demand exists, the heat can be used, if not it constitutes a loss. In this thesis it is assumed to be a loss. H18-DBT has a hydrogen storage density of 6.2wt%.

Hydrogenation:

$$\mathrm{H_0{-}DBT} + 9\,\mathrm{H_2} \rightleftharpoons \mathrm{H_{18}{-}DBT} \qquad \Delta \mathrm{H_R}{=}-65\,\mathrm{kJ/mol}$$



Dibenzyltoluene (H0-DBT) Perhydro-Dibenzyltoluene (H18-DBT)

Figure 2: Simplified reversible reaction for dibenzyltoluene

At the end of LOHC-based pathways dehydrogenation needs to be conducted. The endothermic reaction that requires temperatures of 310°C and a Pt on C catalyst releases 97% of the hydrogen. The released hydrogen is put to further use, whereas the now unloaded DBT is transported back to its origin for the next transport cycle.

Dehydrogenation:

$$\mathrm{H_{18}{-}DBT} + 9\,\mathrm{H_2} \rightleftharpoons \mathrm{H_0{-}DBT} + 9\,\mathrm{H_2} \qquad \Delta \mathrm{H_R}{=}+65\,\mathrm{kJ/mol}$$

Both H18-DBT and H0-DBT are liquid at ambient pressure and normal temperatures. They show similar properties as crude oil based liquids but require less safety measures in handling [59].

4.3.1 LOHC hydrogenation and dehydrogenation

DBT can be seen as the carrier substance for hydrogen, which ideally cycles back and forth between hydrogenation station and dehydrogenation station. Consequently, there is a one time investment in the DBT (assumed lifetime $t = 20$ years). The amount of DBT needed then for the one time investment depends on the quantity of hydrogen Q but also on the length of the transport routes. Within one year, DBT can be cycled several times, therefore the quantity of DBT needed is notably less than the quantity of DBT that would be needed if the whole annual quantity of hydrogen Q would have to be transported at once. With shorter transport routes (as shorter transport takes less time) and smaller Q, DBT can go through more cycles and therefore less DBT is needed overall. The longer the transport distance (with Q held constant or increasing Q), the more DBT is needed. It is not possible to represent this in the model of this thesis, as the conversion and transport steps are treated separately and do not inform each other. Thus, the strong assumption is being made that the amount of DBT needed is half the amount of DBT needed if there was no circulation back (factor 0.5).

The annual costs of hydrogenation and dehydrogenation per kg of hydrogen C_{kg} are calculated according to Reuß et al. and Runge et al. [68, 69], they follow the basic structure depicted in 3.3. The main data used as input is summarized in table 4[2].

[2] LOHC_hyd_DBT refers to the investment cost for the carrier substance DBT

Table 4: Data summary for the LOHC hydrogenation and dehydrogenation plants

Technology	Factor	Unit	mean	min	max
LOHC_Hyd	LOHC_hyd_DBT	euro/kg	3.79	3.79	3.79
LOHC_Hyd	LOHC_hyd_TOMC	% of CAPEX	3.5	3	4
LOHC_Hyd	LOHC_hyd_ElectricityUse	kWh/kg	0.33	0.02	0.6
LOHC_Hyd	LOHC_hyd_Loss	%	1.33	0	3
LOHC_Hyd	LOHC_hyd_t	years	20	20	20
LOHC_Dehyd	LOHC_dehyd_TOMC	% of CAPEX	3.5	3	4
LOHC_Dehyd	LOHC_dehyd_ElectricityUse	kWh/kg	0.52	0	1.18
LOHC_Dehyd	LOHC_dehyd_GasUse	kWh/kg	11.08	9	12.54
LOHC_Dehyd	LOHC_dehyd_Loss	%	0.5	0	1
LOHC_Dehyd	LOHC_dehyd_t	years	20	20	20

4.4 Ammonia

Ammonia NH_3 is a colorless and toxic gas that is soluble in water and has a pungent, readily detectable odor. Ammonia is the precursor of all industrialized nitrogen fertilizers, which makes it an important inorganic industrial chemical. Each year, around 110 million tonnes of nitrogen fertilizer are produced [81]; ammonia is the second most produced industrial chemical behind sulfuric acid [55, 52]. Whereas in the U.S. anhydrous ammonia is directly applied onto the fields, in Europe it is more common to convert it into ammonium nitrate and calcium ammonium nitrate before application [81]. Besides its use as fertilizer, ammonia also has properties that make it an excellent hydrogen storage and transport medium: The industry has decades of experience in large-scale ammonia synthesis through the Haber-Bosch-process. Ammonia transport - though potentially dangerous due to the toxicity of the gas - is well-developed. Ammonia is liquid at 239.8 K (under atmospheric pressure), which makes the transport and storage of liquid ammonia easier than the transport and storage of liquid hydrogen that is only liquid below 21.15 K. Due to molecule packing, ammonia has a higher volumetric energy content than liquid hydrogen (107 kgH2 per m^3 ammonia (gas))[55].

Ammonia can be used in direct application without reconversion into hydrogen, for example in ammonia vehicles that are propelled by reciprocating engines or electricity generated by a solid oxide fuel cell that uses ammonia [52] and gas turbines. This application of ammonia is not considered in this study, as the defined system boundaries require the pathways to start and end with pure hydrogen. For the same reason, ammonia production methods that use water (vapour) instead of hydrogen as an input such as electrochemical production or catalytic reduction are not part of this analysis. They are also not yet economic [52]."Green" ammonia produced with hydrogen from renewable sources offers emission-reduction potential, as traditional ammonia production uses natural gas or oil. 'Green' ammonia as fertilizer is discussed in the scientific literature [81] and would pose a competing end-use to an application as an energy carrier, but it is not further considered in this study.

Figure 3 shows the basic components of the ammonia pathway. It starts with ammonia conversion that consists of two components: the air separation unit (ASU) and the Haber-Bosch loop. Ammonia exits the Haber-Bosch loop in a liquid state which is ideal for transport. At

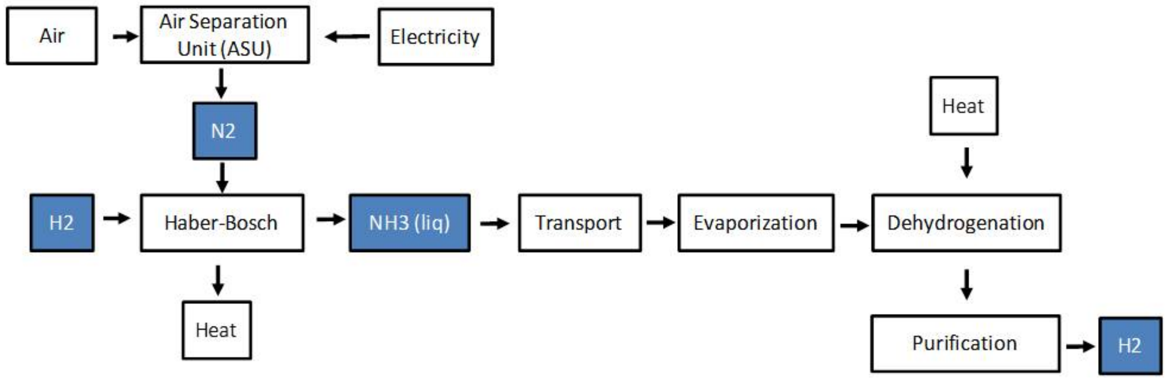


Figure 3: Scheme of the ammonia pathway

the end of the pathway ammonia has to be evaporated and dehydrogenated to regain the hydrogen "stored" in the ammonia. In order to be able to use the hydrogen in all applications, a purification step is required.

4.4.1 Ammonia conversion

The production of ammonia requires two main inputs: hydrogen and nitrogen. While the origin of the hydrogen is not further regarded in this study (system boundaries), nitrogen first has to be distilled from air in an air separation unit (ASU).

Nitrogen production in Air Separation Unit There are three main methods of producing nitrogen from air: cryogenic distillation, pressure swing adsorption and membrane separation. According to Morgan, Manwell, and McGowan [55] and Obara [60], cryogenic distillation is the most economic at high throughput, it accounts for over 90% of nitrogen production and consumes the least amount of energy [89]. Eric R. Morgan states: "Large volumes of ultra-pure gaseous nitrogen can only economically and realistically be achieved using cryogenic air separation." [24, p. 178]. Therefore, cryogenic distillation is chosen in this study for nitrogen production. The process is based on boiling point differences between the main constituent gases of air, namely nitrogen, oxygen and argon. It is highly non-linear and complex but fortunately already well understood and commercialized.

Haber-Bosch There are other forms of ammonia production than the Haber-Bosch loop (HB). Al-Zareer, Dincer, and Rosen propose a pressurized subzero-cooled ammonia production system (PSAPS) [4]. But to date the Haber-Bosch process is by far the most developed and most studies analyzing ammonia as an energy carrier/hydrogen medium focus on Haber-Bosch [1, 5, 10, 14, 16, 32, 37, 47, 52, 55, 81, 88, 93], therefore this process was chosen in this study. Nitrogen and hydrogen are fed into the Haber-Bosch synthesis loop in a ratio of 1:3. This mixture called synthesis gas is first compressed to 120-220 bar depending on the plant and then fed into the synthesis loop where nitrogen reacts with the hydrogen in an exothermic reaction that releases $\sim 92.5kJ/mol$ at temperatures between 653 K and 800 K. For this reaction, a catalyst is used. An iron catalyst promoted with K_2O or Al_2O_3 is common, in modern converters ruthenium-based catalysts are also employed [14].

$N_{2(g)} + 3\,H_{2(g)} \longrightarrow 2\,NH_{3(g)} \qquad \Delta H^\circ{}_f = -\,92.5\,kJ$

As only a fraction of the synthesis gas reacts during every pass through the gas is passed through several times in a loop to achieve higher overall conversion efficiency. After the conversion section of the plant, the syngas-ammonia mixture enters the separation section, where refrigeration coolers cool the mixture down to 263.15 K and 248 K to separate the ammonia. Impurities are also removed. Following this loop-mode production, an overall conversion efficiency of 98% can be achieved [93]. This process is designed for continuous mass production, however dynamic production if necessary is assumed feasible [37].

Ammonia Liquefaction Ammonia is liquid at 250.15 K, which is 229 K warmer than liquid hydrogen. The liquefaction is already part of the Haber-Bosch synloop so that no extra liquefaction is needed if ammonia is to be transported in a liquid state from the plant.

Cost calculation ammonia conversion The cost calculations follow the basic structure depicted in chapter 3.3. $CAPEX$ consists of $CAPEX_{ASU}$ and $CAPEX_{HB}$, $OPEX$ is mainly influenced by $TOMC$ and the electricity costs required for both ASU and the Haber-Bosch synloop. The calculations follow Ikäheimo et al. [37] and Wijayanta et al. [93]. The main data used as input for both ammonia conversion and reconversion is summarized in table 5.

4.4.2 Ammonia reconversion

At the end of the transport, ammonia is reconverted into nitrogen and hydrogen. This endothermic reaction is relatively simple:

$2\,NH_{3(g)} \longrightarrow N_{2(g)} + 3\,H_{2(g)}$

Due to its endothermic nature, the reaction needs higher temperatures and/or catalysts. "Ammonia is thermodynamically unstable at high temperatures as it begins to decompose at $\sim$ 200°C. The equilibrium conversion of ammonia to hydrogen and nitrogen is 98-99% at 425°C with the practical conversion of ammonia highly dependent on both temperature and catalyst. At a temperature above 500°C, thermal decomposition of ammonia is significant even without catalysts." [47, p. 1487]. In contrast to ammonia conversion, ammonia reconversion is far less widely applied. The cracking systems are still under development, with new catalyst-temperature combinations being advanced. Lamb, Dolan, and Kennedy [46] and Mukherjee et al. [56] give detailed overviews on the advantages and disadvantages of various methods. All methods have in common that residues of ammonia remain in the hydrogen gas. This is problematic for polymer electrolyte membrane fuel cell (PEMFC) vehicles that require a purity of > 99.99% [32] with less than 100 part per million by volume (ppmv) of N_2 and 100 ppbv of NH_3 [46]. Therefore, further hydrogen purification or scrubbing is required to achieve pure hydrogen. As ammonia reconversion is still in a development phase, cost estimations are dif-

Table 5: Data summary for the NH3 hydrogenation and dehydrogenation plants

Technology	**Factor**	**Unit**	**mean**	**min**	**max**
NH3_Hyd	NH3_HB_TOMC	% of CAPEX	2	2	2
NH3_Hyd	NH3_hyd_ElectricityUse	kWh/kg	0.64	0.64	0.64
NH3_Hyd	NH3_ASU_ElectricityUse	kWh/kg	0.25	0.06	0.51
NH3_Hyd	NH3_HB_ElectricityUse	kWh/kg	0.54	0.44	0.64
NH3_Hyd	NH3_hyd_Loss	%	2	2	2
NH3_Hyd	NH3_hyd_t	years	20	20	20
NH3_Dehyd	NH3_dehyd_TOMC	% of CAPEX	4	4	4
NH3_Dehyd	NH3_dehyd_ElectricityUse	kWh/kg	11.2	11.2	11.2
NH3_Dehyd	NH3_dehyd_Loss	%	15.85	15.85	15.85
NH3_Dehyd	NH3_dehyd_t	years	20	20	20

ficult. A detailed analysis of all plant components and monetarization with the The Chemical Engineering Plant Cost Index (CEPCI) as performed for example by Morgan, Manwell, and McGowan [55] would exceed the scope of this analysis. Therefore, the calculations presented here rely on the cost estimates by the International Energy Agency [85], energy requirements are taken from Giddey et al. [32].

Purification Two methods are available to clear the hydrogen from any residues: Pressure swing adsorption (PSA) and polymeric, metal or ceramic membranes. With PSA the gas is pressed through a selectively absorbent material (carbon, silica or zeolites). Then the stream is reversed, so that unwanted gasses are flushed out. Disadvantages of this system are the necessity to reverse the stream, resulting in relatively low efficiency and the need for several PSA-units in one plant. Still, this is to date the only off-the-shelf solution [32]. PSA is also the hydrogen purification method used in the analysis by the IEA. To stay congruent, PSA is chosen in this study.

Cost calculation ammonia reconversion The cost calculations follow the basic structure depicted in chapter 3.3. The main data used as input for both ammonia conversion and reconversion (except BaseCost) is summarized in table 5.

4.5 Trucks

The method for calculating energy efficiencies and costs for truck transport is based on André et al. and Lahnaoui, Wulf, and Dalmazzone [9, 43, 45]. It is assumed that semi-trailer trucks[3] are used for all media. Semi-trailer trucks consist of two major units: the tractor unit with the driver's cab and a trailer that mounts the tractor. Truck refers to the combination of tractor and trailer. Further simplifying assumptions are:

- All media use the same tractor unit and different trailers.

[3] Also known as semi trucks or semis, in Germany known as Sattelkraftfahrzeug; in Austria Sattelzug.

- The empty trucks drive back, therefore every distance is driven twice.
- Fuel demand does not change with freight load.
- During loading and unloading the driver is present and waiting at the truck.
- Trucks use existing infrastructure (roads, fuel stations etc.) whose costs are not taken into account.

The cost and energy efficiency calculations use the structure of chapter 3.3. Total Fuel Costs are calculated using the diesel price, truck consumption, twice the transport distance L as trucks drive back and the number of round trips in one year the truck can make N_{rt}.

$$TFC_{truck} = FuelPrice_{truck} \cdot Consumption_{truck} \cdot 2 \cdot L \cdot N_{rt} \tag{10}$$

Total Labor Costs depend on the driver's wage, the triptime and the number of round trips in one year N_{rt}.

$$TLC_{truck} = DriverWage \cdot triptime \cdot N_{rt} \tag{11}$$

N_{rt} is calculated as follows:

$$N_{rt} = \frac{8760h \cdot Availability_{truck}}{triptime} \tag{12}$$

Triptime is the time needed for one round trip. It is based on the distance, the truck's speed, unload time and load time.

$$triptime = 2 \cdot \frac{L}{Speed_{truck}} + LT_{truck} + ULT_{truck} \tag{13}$$

In order to calculate the overall costs per kg of hydrogen C_{kg}^{truck} for all four kinds of truck transport, the transported yearly quantity per truck Q_a^{truck} is calculated (and not pre-defined). For transport media with boil-off the evaporated quantity has to be subtracted.

$$Q_a^{truck} = N_{rt} \cdot Capacity \cdot (1 - \frac{boiloff}{100})^{\frac{triptime - LT_{truck} - ULT_{truck}}{24h \cdot 2}} \tag{14}$$

4.5.1 Cost assumptions for all truck types

For the sake of comparability, it is important to define assumptions for truck cost components that concern every medium so that costs only vary in the substantial cost components (load times, trailer aspects, boil-off rates...). They are defined in table 6.

4.5.2 Compressed hydrogen trucks

For the transport of gaseous hydrogen with trucks, the hydrogen gas is compressed to several pressure levels and stored in cylindrical vessels. These vessels, so-called tubes, are then

Table 6: Data summary for all truck types and the tractor

Technology	Factor	Unit	mean	min	max
AllTrucks	Tractor_Invest	euro	173508.28	133678.91	237521.66
AllTrucks	Tractor_TOMC	% of CAPEX	12	12	12
AllTrucks	Consumption	liter/km	0.37	0.3	0.43
AllTrucks	Speed	km/h	52.5	50	55
AllTrucks	Availability	% of CAPEX	77.5	75	80
AllTrucks	Driver Wage	euro/h	29.48	13.9	45.92
AllTrucks	FuelPrice	euro/liter	1.45	1.23	1.87
AllTrucks	Tractor_t	years	11.25	5	20

mounted on a trailer. This creates the typical tube trailer appearance. The transported quantity depends on the pressure level in the tubes. Pressure levels range from 200 bar to 500 bar with transport capacities ranging from 400 kg up to 1200 kg [7, 9, 13, 85, 43, 44, 45, 68, 76, 82, 83, 98, 66, 65]. According to Reddi et al. [66], there are two main types of tubes: steel tube trailers and composite tube trailers. For high pressure levels, the main disadvantage of steel tubes is their weight. As the tube walls have to contain higher pressures, the wall thickness increases and the tubes become considerably heavier. This limits the overall capacity of steel tube trailers.

Composite tubes on the other hand allow pressure levels of up to 500 bar as they are much lighter. Composite tube trailers are also more expensive. In extensive analyses, Lahnaoui et al. and Reddi et al. [45, 66] compared various trailer configurations. They both conclude that composite tube trailers with high capacities and high pressure levels become the most economic option for long distances.

> *As the transportation distance or station capacity increases, the economics shift toward higher payload. [Therefore,] the economics of hydrogen delivery favor the composite vessel tube trailers at higher market demands and longer transportation distances [66, p. 4437]. At high demand and for more than 100 km trip distance, the hydrogen is transported using almost only CGT at 540 bar reflected by a share of 98-99% [45, p. 8].*

For this reason, it is assumed that the gaseous hydrogen is transported in large semi-trailers at 500 bar with composite tube trailers. The relevant cost components are listed in table 7.

Table 7: Data summary for compressed hydrogen trucks

Technology	Factor	Unit	mean	min	max
CG_Trucks	Trailer_Invest	euro	1010801.04	206811.41	1737825.87
CG_Trucks	Trailer_TOMC	% of CAPEX	2	2	2
CG_Trucks	Capacity	tonH2/trailer	1.01	0.65	1.3
CG_Trucks	Boil-Off	%/day	0	0	0
CG_Trucks	LoadTime/UnloadTime	h/trip	1.5	1	2
CG_Trucks	Trailer_t	years	12	12	12

4.5.3 Liquid hydrogen trucks

For the transport of liquid hydrogen, cryogenic hydrogen trucks are needed. They consist of a vacuum-jacketed cryogenic tank that is mounted on a trailer, similar to those used for the transport of LNG or liquid helium. The trailers have a capacity of 4000 kg of hydrogen. While all sources [85, 68, 9, 7, 67, 83, 76, 98, 65] are consistent in the capacity assumption (4000 kg to max. 4300 kg), they show a wide range in the CAPEX assumption. One main concern in cryogenic transport is the boil-off. Boil-off describes the daily loss of hydrogen that occurs because some hydrogen evaporates and has to be vented off to maintain the pressure level, therefore the boil-off constitutes a steady loss during transportation. Typical hydrogen boil-off rates lie around 0.2 - 0.5% per day. All cost components for liquid hydrogen trucks are listed in table 8.

Table 8: Data summary for liquid hydrogen trucks

Technology	**Factor**	**Unit**	**mean**	**min**	**max**
LIQ_Trucks	Trailer_Invest	euro	678543.46	369236.03	1061942.71
LIQ_Trucks	Trailer_TOMC	% of CAPEX	2	2	2
LIQ_Trucks	Capacity	tonH2/trailer	4.08	3.5	4.37
LIQ_Trucks	Boil-Off	%/day	0.93	0.3	3
LIQ_Trucks	LoadTime/UnloadTime	h/trip	2.5	2	3
LIQ_Trucks	Trailer_t	years	12.67	6	20

4.5.4 LOHC trucks

LOHC have certain advantages that make their transport easier than the transport of other media. Tankers require no insulation and no high pressures and there is no loss during transport and storage even over longer periods. This means that relatively simple tank trailers can be used so that the $CAPEX$ is significantly lower than the $CAPEX$ cost of liquid hydrogen trailers. All costs assumptions are listed in table 9, they are taken from the International Energy Agency, Reuß et al. and Teichmann, Arlt, and Wasserscheid. Furthermore, data has been obtained from the first provider of LOHC storage and transportation solutions in Germany hydrogenious [85, 67, 68, 83, 74]. As the carrier medium DBT has to be loaded, driven back to the hydrogen source and unloaded, LoadTime and UnloadTime have to be taken twice. See table 9 for all assumptions.

Table 9: Data summary for LOHC trucks

Technology	**Factor**	**Unit**	**mean**	**min**	**max**
LOHC_Trucks	Trailer_Invest	euro	120333.5	50000	180530.26
LOHC_Trucks	Trailer_TOMC	% of CAPEX	2	2	2
LOHC_Trucks	Capacity	tonH2/trailer	1.74	1.5	2
LOHC_Trucks	Boil-Off	%/day	0	0	0
LOHC_Trucks	LoadTime/UnloadTime	h/trip	1.88	1	3
LOHC_Trucks	Trailer_t	years	12.67	6	20

4.5.5 Ammonia trucks

Information on trailers for the transport of ammonia is scarce in scientific literature. Thus, the main source of information are two telephone interviews with Carina Meyer (26.06.2020, approximately 30min, 27.02.2020, approximately 15 min), who is the contact person overseas and responsible for tank container rental at Hoyer GmbH [50]. Furthermore, the IEA include ammonia trucks in their report, this data is also part of this analysis [85]. Ammonia can be transported in several states, for example liquid or as a salt. Hoyer GmbH uses tank containers for liquid anhydrous ammonia, thus this technology is chosen in this analysis. Due to its properties described in chapter 4.4, ammonia transport poses risks and is for example regulated in the GGVSEB 2009 (Gefahrgutverordnung Straße, Eisenbahn und Binnenschifffahrt) in Germany and in the ADR ECE/TRANS/275 of September 1957 (European Agreement concerning the International Carriage of Dangerous Goods by Road) for the European Union. According to Hoyer GmbH, tank containers that are mounted on a chassis are most common, as these tank containers can be easily transferred on a train freight car. This modality is important due to the regulations for dangerous goods. Therefore, trailer costs are calculated as the costs for the chassis plus the cost for the tank container. All data is summarized in table 10.

Table 10: Data summary for ammonia trucks

Technology	**Factor**	**Unit**	**mean**	**min**	**max**
NH3_Trucks	Trailer_Invest	euro	115819.26	52172.26	233627.4
NH3_Trucks	Trailer_TOMC	% of CAPEX	2	2	2
NH3_Trucks	Capacity	tonH2/trailer	2.41	2.31	2.6
NH3_Trucks	Boil-Off	%/day	0	0	0
NH3_Trucks	LoadTime/UnloadTime	h/trip	1.5	1.5	1.5
NH3_Trucks	Trailer_t	years	20	20	20

4.6 Pipeline

The main cost components of pipelines are material costs, installation costs, costs for the land where the pipeline is build (or the right to use it), operation and maintenance costs and compressor/pump costs. Compressors need to be installed at equal intervals along the transmission pipeline as the gas looses pressure due to friction on the internal wall of the pipe [8, p. 241]. The cost components referring to material, installation and land are often summarized in one $CAPEX_{pipe}$ equation. The factor that has by far the most influence on $CAPEX_{pipe}$ is the diameter d of the pipe. In theory, compressed hydrogen gas, ammonia, LOHC and methane pipelines are relevant modes. Liquid hydrogen pipelines would require intense cooling and pumping efforts and high insulation costs.

4.6.1 Hydrogen pipeline

There are numerous estimations of $CAPEX_{pipe}$ for hydrogen pipelines which use the pipe diameter. They adapt data from natural gas pipelines to fit hydrogen pipelines, mostly taking into account the use of different materials (for inside coating) and different installation procedures [7, 8, 9, 15, 19, 85, 40, 61, 68, 98, 75]. Unfortunately, the equations vary greatly and show very little congruence. In the following, all equations that were used in the analysis are listed, they stem from the following sources: André et al., Reuß et al., Yang and Ogden, Baufumé et al., Castello et al., Penev, Zuboy, and Hunter, Moreno-Benito, Agnolucci, and Papageorgiou, Heuser et al. In their original form, they use different units for the diameter and different currencies, therefore, they were all adapted to €2015 and the diameter in mm:

$$\begin{aligned}
\text{André2014} &: 629746.13 + 1146.83 \cdot d + 3.47 \cdot d^2 \\
\text{Reuß2019} &: 306367 \cdot e^{0.0016 \cdot d} \\
\text{YangandOgden2007} &: 475043.33 + 4.59 \cdot d^2 \\
\text{Baufume2013a} &: 267596.5 + 606.01 \cdot d + 1621.8 \cdot d^2 \\
\text{Baufume2013b} &: 355714.13 + 647.21 \cdot d + 3.67 \cdot d^2 \\
\text{Castello2005} &: 724660.06 \cdot d - 3.73 \cdot d^2 \\
\text{Penev a} &: 17156.38 \\
\text{Penev b} &: 10557.77 \\
\text{Penev c} &: 51469.13 \\
\text{Penev d} &: 124053.79 \\
\text{MorenoBenito2016} &: 261.58 \cdot d \\
\text{Heuser2019} &: 234775.18 + 815.78 \cdot d + 2.09 \cdot d^2
\end{aligned}$$

Cost and energy efficiency calculations follow the basic structure outlined in chapter 3.3. As explained above, the $CAPEX_{pipe}$-equations are given per km and depend on the diameter of the pipe d. Hence, investment costs for the whole pipeline from start to end depend on d and the length of the pipeline which is the transport distance L. The yearly quantity of hydrogen transported through the pipe is calculated using the mass flow rate $\dot{Q}_{mass}$ in kg/s of hydrogen through the pipeline at an average delivery pressure of 65 bar [15]:

$$\dot{Q}_{mass} = \rho \cdot v \cdot \frac{\pi \cdot (d \cdot 1000)^2}{4} \tag{15}$$

where ρ is the mass density and v the average fluid velocity.The transported yearly quantity is calculated ($n_{seconds/a}$ is number of seconds in a year):

$$Q_a^{pipe} = \dot{Q}_{mass} \cdot n_{seconds/a} \cdot Availability \tag{16}$$

According to Baufumé et al. [15] a recompression station is necessary after every 250 km of pipeline as the gas loses pressure in the pipe. The necessary adiabatic work $\dot{W}^t_{\Delta S->0}$ for the recompression is calculated as outlined in chapter 4.1, with the assumption that the average temperature in the pipeline is constant at 293.15 K [19, p. 38] and the compressibility factor Z that depends on the starting pressure $P_{in} = 30bar$ approximated to $Z = 1.02$ [41, p. 4.170]. It is further assumed that the costs for the recompression station is already part of the $CAPEX$-stations, although not all sources affirm that explicitly. The electricity used for the recompression is included in the total input costs (TIC) of the pipeline and defines the energy efficiency of the pipeline.

TOMC costs range between 2 and 5% of CAPEX per year, the estimated lifetime ranges between 40 and 50 years.

4.6.2 LOHC pipeline

It can be argued that LOHC pipelines would be similar to crude oil pipelines, due to roughly similar physical and chemical properties. LOHC pipelines do not exist and are hence difficult to model. The main complication of LOHC pipelines is that the carrier medium has to be transported back in a separate pipeline if a continuous hydrogen flow is the goal, consequently all investments and energy inputs double. Accordingly, it was concluded that LOHC pipelines are not competitive to hydrogen pipelines and they are excluded from this analysis.

4.6.3 Ammonia pipeline

Morgan et al. note that “liquid ammonia also boasts a vast pipeline infrastructure in the Midwest ranging from New Orleans to Minnesota and from Texas to Indiana.” [55] This is due to the fertilizer network in agricultural hotspots. In contrast, no ammonia pipeline could be found for Europe. Data on costs and energy requirements for ammonia pipelines is scarce. Leighty et al. [48] mention a cost equation based on the diameter of the pipeline for ammonia pipelines, but they “assume that NH3 pipelines, and GH2 pipelines fit for renewables-hydrogen service, can be built for the same cost as NG pipelines of the same diameter and rated pressure, assuming no incremental capital costs for GH2-capable line pipe, valves, and meters.” [48, p. 335]. Given the chemical and physical differences between natural gas and liquid ammonia, this assumption is contested. Bartels analyses ammonia pipelines in a master thesis [14], but does not include investment costs.

Due to these difficulties in the data quality, ammonia pipelines were not included in this model.

4.7 Ships

Liquid hydrogen, LOHC and ammonia can be transported with carriers over water. The cost calculations for ships are similar to the truck calculations: the main cost components are the ship investment cost $CAPEX_{ship}$ and fuel costs. Two telephone interviews with ship logistics experts within the industry were essential sources of information for the inclusion of ship transport in this model: one with Tor Øyvind Ask, Fleet Director at Solvang ASA (05.11.2019, approximately 15min) on technical specifications of medium and large gas carriers [49] and one with Michael Rufian, Head of Client Service at vesselsvalue on the delivery price of gas carriers and tankers (31.10.2019, approximately 15min) [51]. For the sake of comparability of the ships three simplifying assumptions were made:

- all ships are propelled with heavy fuel oil as according to Solvang ASA [49], this is standard industry practice and most ships run on heavy fuel oil (HFO).
- The actual transportable cargo weight is 90% of a ship's deadweight (dwt) [28]
- In harbour/ at a terminal during loading and unloading ships also use HFO as their fuel and not supplementary fuels that are required in some harbours due to environmental regulations.

In general, calculations follow the structure in chapter 3.3. The number of round trips N_{rt}, $triptime$ and yearly transported quantity per ship Q_a^{ship} are calculated as in chapter 4.5. The calculation for total fuel use and total fuel costs TF, TFC and ConvTransE are slightly different, as for ships, fuel consumption is mostly given in tons per day and there is fuel consumption during unloading and loading. Equation 17 shows the calculation for TFC; TF and ConvTransE calculations are modified accordingly. For liquid hydrogen carriers the consumption is given in MJ/km, thus the equation changes slightly (see equation 18) and uses the lower heating value (LHV) for HFO. The total distance the ship travels is calculated as $2 \cdot L \cdot N_{rt}$ as we assume that empty ships travel back, thus doubling the travelled distance.

$$\begin{aligned} TFC^1_{ship} = (&FuelPrice_{HFO} \cdot Consumption_{shipping} \cdot \frac{triptime}{24h} \cdot N_{rt})+ \\ &(FuelPrice_{HFO} \cdot (Consumption_{LT,ULT} * \frac{(LT+ULT)}{24h}) \cdot N_{rt}) \end{aligned} \tag{17}$$

$$\begin{aligned} TFC^2_{ship} = (&FuelPrice_{HFO} \cdot Consumption_{shipping} * 2 * L * N_{rt} * \frac{1}{LHV})+ \\ &(FuelPrice_{HFO} \cdot (Consumption_{LT,ULT} * \frac{(LT+ULT)}{24h}) \cdot N_{rt}) \end{aligned} \tag{18}$$

Some basic assumptions will be the same for all ship types, they are defined in table 11.

Table 11: Data summary for all ship types

Technology	**Factor**	**Unit**	**mean**	**min**	**max**
AllShips	LoadTime/UnloadTime	h	24	24	24
AllShips	Consumption_Un_Loading	t/day	6	6	6
AllShips	Speed	km/h	30.5	26	33
AllShips	Availability	%	98.75	95	100
AllShips	Ship_t	years	26.67	25	30
AllShips	Ship_TOMC	% of CAPEX	3.8	2.8	5

4.7.1 Liquid hydrogen tankers

Liquid hydrogen carriers do not exist yet. Their design poses more difficulties than LNG carriers, as the very low temperature of 21.15 K has to be maintained throughout transport. Kamiya et al. developed a concept design of a 11.328 tons hydrogen carrier [42] which will be used in this study. The carrier uses the boil-off as fuel for the hydrogen gas engine. Cost calculations will furthermore be based on assumptions by Balat et al. and the IEA [12, 85]. They are summarized in table 12. The gross tonnage assumption is based on the 160,000 cbm LNG carrier Cool Explorer (IMO 9640023).

4.7.2 LOHC tankers

Simple crude oil carriers can be used for the shipping of LOHC according to Teichmann et al. [83]. That is a cost advantage, as these ships require neither cooling nor pressurizing and are very common. Furthermore, existing port infrastructure can be used for the handling. As with LOHC trucks, ships have to transport unhydrogenated DBT back, so that LoadTime and UnloadTime have to be doubled. Crude oil carriers come in a wide range of sizes and make for the largest tankers in the world: Ultra Large Crude Carriers (ULCC) can transport up to 440,000 dwt (deadweight tons, total maximum weight a ship can carry, including cargo, fuel, water, people etc.) [94, p. 148f]. Their size also poses a disadvantage, as they cannot pass neither the Suez canal nor the Panama canal and can only be handled at a few ports worldwide. In contrast to ULCC and VLCCs (Very Large Crude Carriers), Aframax tankers with a deadweight between 80,000 and 120,000 dwt can enter most ports and marine areas such as the North Sea. The IEA [85] and Fasihi et al. 2016 [28] both assume an Aframax tanker in their calculations; which is also the carrier size Michael Rufian [51] judges to be realistic. Therefore, the cost calculations will be based on a 105,000 dwt Aframax tankers, specifications are listed in table 12. The Consumption is based on the crude oil tanker Phoenix Hope by Hyundai (IMO 9390587), that was delivered in 2008 [94, p.156]. As Teichmann et al. [83] use Handysize tankers at 45,000 dwt, a handysize tanker was also included.

4.7.3 Ammonia tankers

Ammonia carriers are tankers in the LPG-carrier category. They transport their cargo at 223 K and under atmospheric pressure. Ammonia carriers are handled at special LPG terminals [94, p.171f]. Different to non-refrigerated tankers, the size of LPG-carriers is given in cbm, the size of the tanks in cubic meters. Shipping companies publish data on their LPG-carriers and chemical carriers on their websites in the form of technical data sheets. Therefore, the ammonia tanker technical specifications (mainly consumption and capacity) could be taken from them [35, 34, 90, 79, 78]. Three size categories of ammonia tankers were included in this analysis: Large Gas Carriers (LGC), Medium Gas Carriers (MGC) and Handysize. The main assumptions are summarized in table 12.

Table 12: Specific values for all three ship types

Shiptype	Shipsize	CAPEX	CapacityH2	Consumption	boiloff
none	none	euro	tons	MJ/km;t/day	%/d
LIQ_Ship	unspecified	437520394	11000	1487	0.21
LIQ_Ship	unspecified	762284886	10000	1487	0.21
LIQ_Ship	unspecified	149162239	1050	1487	0.21
LIQ_Ship	unspecified	474293302	11360	1487	0.21
LOHC_Ship	Aframax	90265129	6820	35.2	0
LOHC_Ship	Aframax	54477660	3906	35.2	0
LOHC_Ship	Aframax	54477660	5580	35.2	0
LOHC_Ship	Aframax	47880299	5580	35.2	0
LOHC_Ship	Handysize	35758071	2400	46.5	0
NH3_Ship	LGC	80707645	9434	35	0
NH3_Ship	Handysize	43539650	5607	46.5	0
NH3_Ship	Handysize	45663536	5607	46.5	0
NH3_Ship	LGC	67964333	7283.76	35	0
NH3_Ship	MGC	53097135	4248.86	24	0

4.8 Terminals

Carriers and tankers require specialized terminals for loading and unloading cargo. The only ship type in this thesis for which terminals already exist is ammonia tankers, as ammonia transport via sea is already done. LOHC terminals could potentially be modelled after crude oil terminals or specialised terminals for the handling of chemicals and liquids but this is an assumption that could not be backed up with literature. The main challenge lies in the terminals required for liquid hydrogen tankers as they do not exist yet. They could potentially be based on LNG terminals but given the substantial difference in the temperature levels of liquid natural gas and liquid hydrogen, this is a questionable assumption. The only source for CAPEX estimations for terminals is the IEA, who give figures without an explanation [85]. Drennen and Rosthal, Fasihi, Bogdanov, and Breyer, Kamiya, Nishimura, and Harada and Heuser et al. all include ship transport but do not factor in any costs for the terminals [23, 28, 42, 36].

For lack of an alternative, terminals are not part of the calculations for ship transport, although they could potentially influence the costs significantly. At the same moment, while initial installation costs may be very high, the per costs per unit of unloaded medium are probably low due to the very high throughput.

5 Results

In this chapter, the results of the analysis are laid out. Firstly, the results for the complete conversions (all conversions necessary; aC) are presented. Secondly, the modes of transport for land transport and for sea transport are displayed separately. Thirdly, the pathways (p) that consist of one mode of transport and the corresponding conversions are analysed with a focus on final costs. Based on these results, the most competitive pathways were chosen and combined into three combined pathways. Finally, the regression results are presented with the aim of identifying the parameters with the highest influence. For every figure a table that summarizes the most relevant numbers is included in the Appendix.

5.1 Conversions

The conversions included in this model are compression to 100 bar and 500 bar (Comp_100 and Comp_500), liquefaction and evaporation (LIQ_Conv_aC), LOHC hydrogenation and dehydrogenation (LOHC_Conv_aC) and NH3 hydrogenation and dehydrogenation (NH3_Conv_aC). Figure 4 shows the costs per MWh of hydrogen C_MWh of conversion plotted against the annual quantity of hydrogen Q. Overall the costs decrease with higher quantity, which is an expected behaviour due to the scaling factor of around 0.6 that scales the CAPEX costs per plant for higher Q.

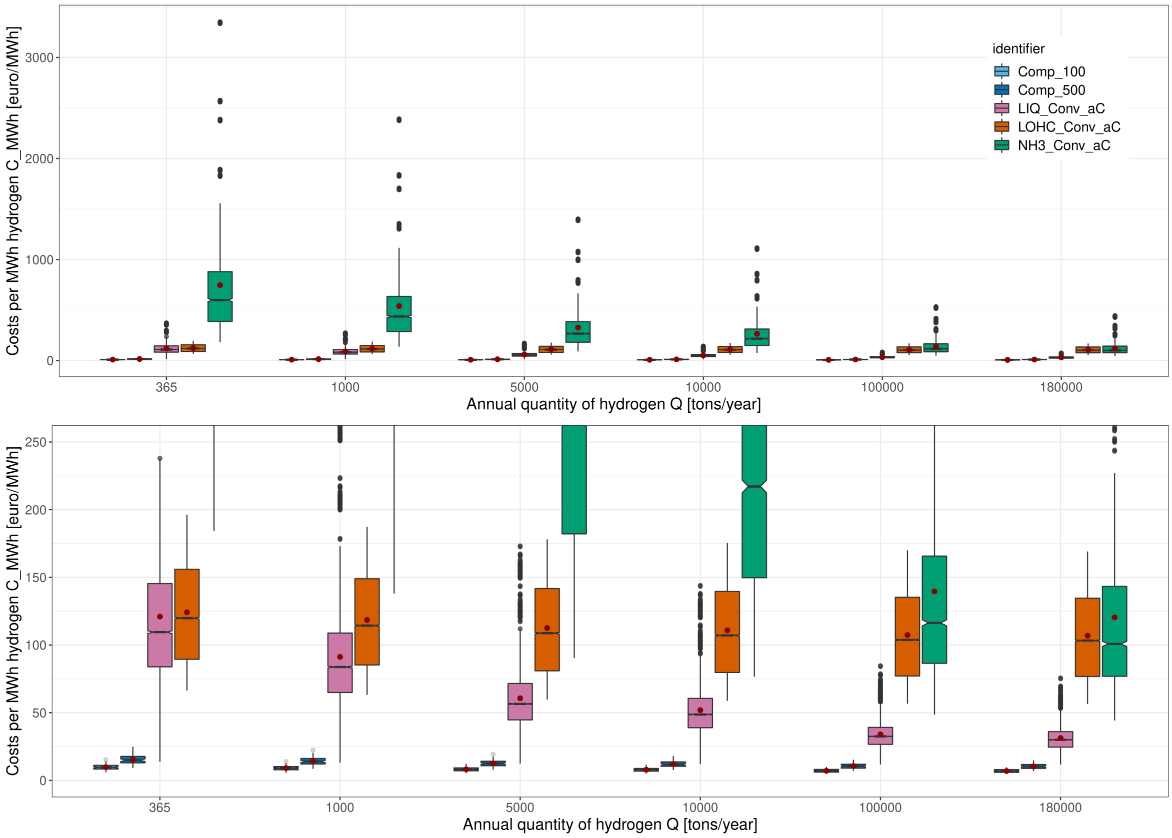


Figure 4: Total conversion costs per medium - the two plots only differ in the y-axis range; the upper plot shows the full range with all outliers, the lower plot zooms into a smaller cost range; the red dot shows the mean

Most notably, the NH3_Conv_aC is substantially more expensive than all other conversions, especially for small quantities. The high outliers at over 2000 €/MWh stem from conversion plants that are designed for a much higher throughput Q and have comparatively high CAPEX costs. They are scaled down to fit a plant with a capacity of 365 tons/year but this method has its limits. Therefore, the very high outliers can be ignored. The two compression plants Comp_100 and Comp_500 are much cheaper than all other conversions. This is because they are comparatively small plants that require a much lower CAPEX. The CAPEX is also proportional to Q so that the median C_MWh hardly declines with higher Q. Based on the notches in the boxplots there is strong evidence that the C_MWh of LIQ_Conv_aC and LOHC_Conv_aC differ even for Q = 365 tons/year [20], so that LIQ_Conv_aC is significantly cheaper for all Q.

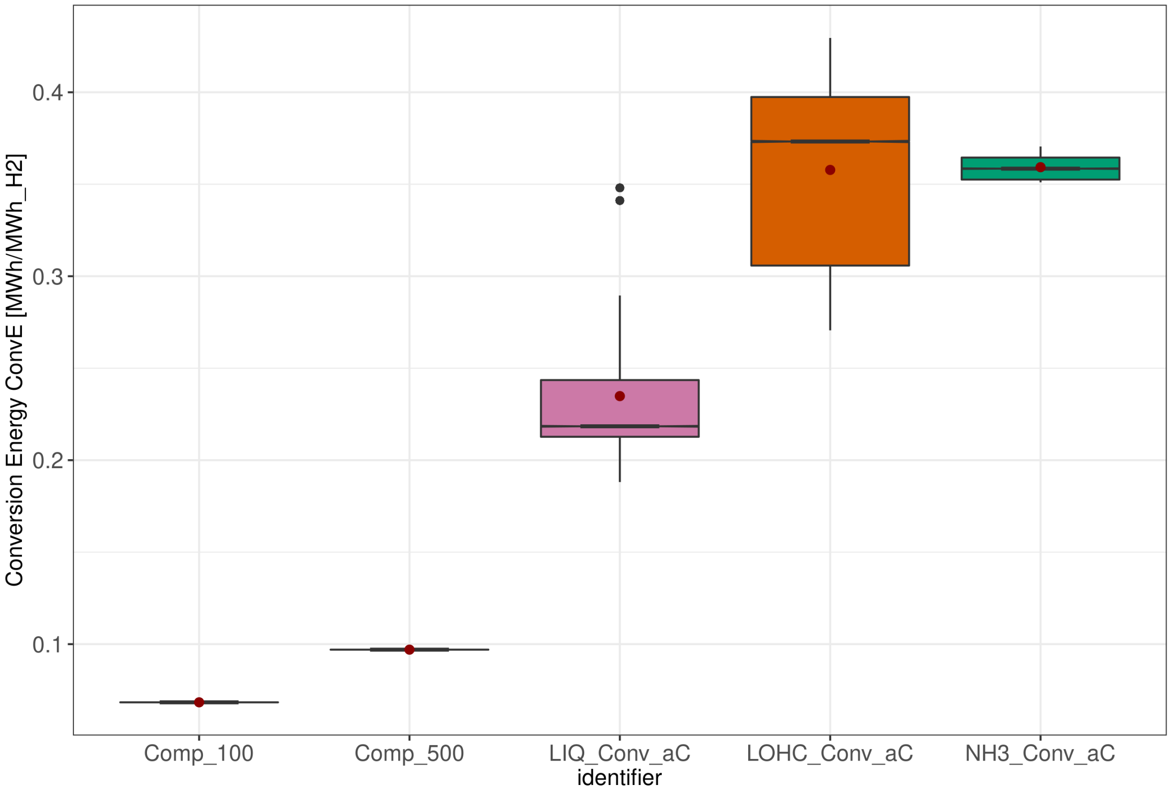


Figure 5: Total conversion energy per medium; the red dot shows the mean

Figure 5 shows the conversion energy ConvE that needs to be invested during the conversion processes. The compressions require only a very low percentage of invested energy relative to the amount of hydrogen in MWh of 6.8% and 9.7%; the compression energy is implemented as a function of Q and the desired pressure level. The liquefaction and evaporation processes in LIQ_Conv_aC require a median of 21.8%. LOHC_Conv_aC has the highest dispersion around the median of 37.32%. NH3_Conv_aC also requires a high energy investment as the median is at 35.8%. This is an important result and should always be considered when comparing mediums as it means that with LOHC- and NH3-pathways over 30% of transported energy is "lost" in the conversion processes. The lowest ConvE of Comp_100 is also an argument for pipeline transport.

5.2 Transport mode

5.2.1 Transport on land

The transport modes for transport over land in this model are compressed gaseous hydrogen trucks (CG_truck), liquid hydrogen trucks (LIQ_truck), LOHC trucks (LOHC_truck), trucks transporting liquid ammonia (NH3_truck) and hydrogen pipelines (pipe).

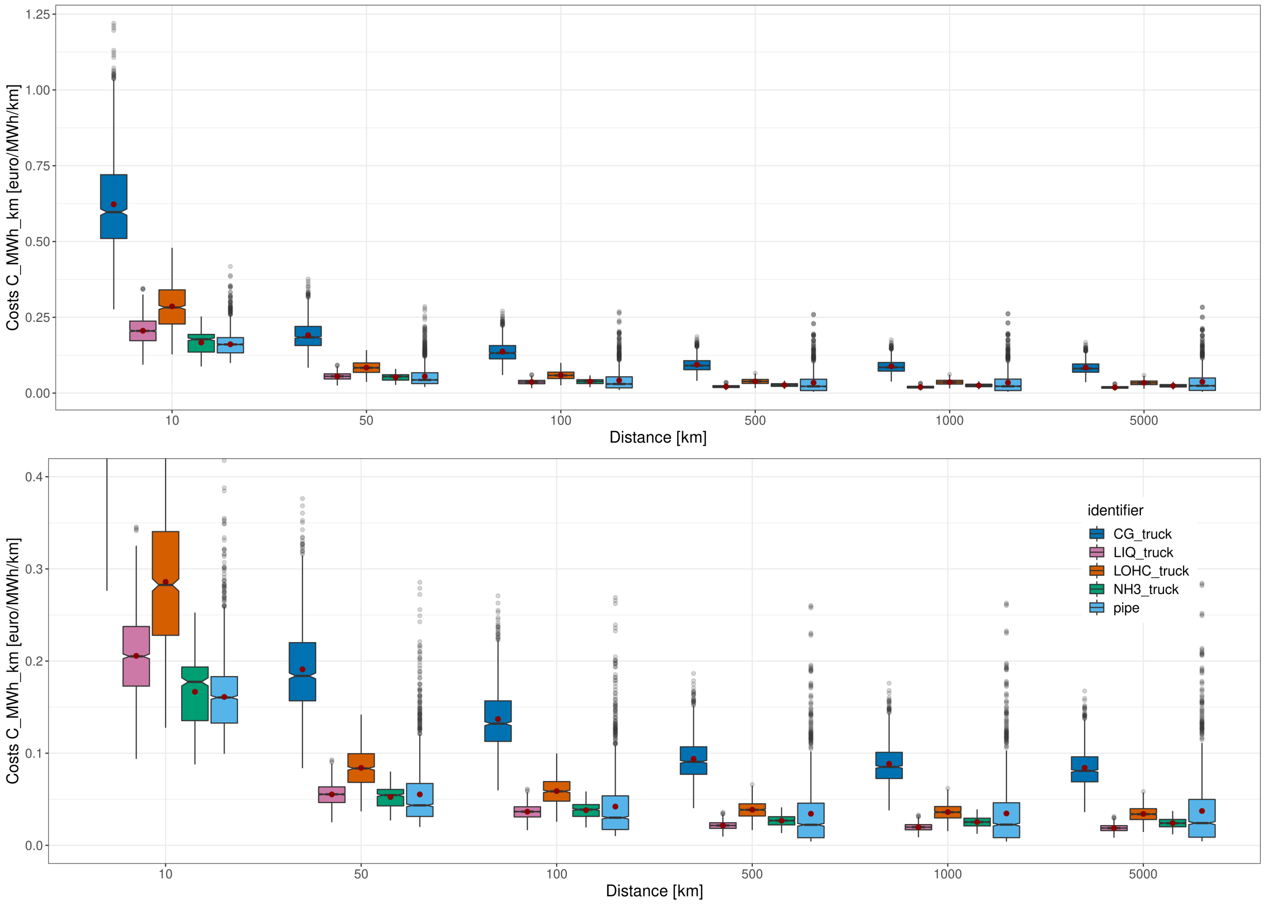


Figure 6: Land: total transport costs per medium C_MWh/km without conversion - the two plots only differ in the y-axis range; the upper plot shows the full range with all outliers, the lower plot zooms into a smaller cost range; the red dot shows the mean

The costs per transported MWh of hydrogen per kilometer per medium C_MWh_km without the conversions are plotted in figure 6, with the transport distance on the x-axis. For all distances, CG_truck is considerably more expensive than all other land transport options. This is mainly due to the low capacity of CG_trucks. Based on the median, LOHC_trucks are significantly more expensive than LIQ_truck, NH3_truck and pipe. For distances over 100 km LIQ_truck, NH3_truck and pipe are highly competitive and show only small differences in C_MWh_km. When comparing these three transport modes it is important to note that pipelines have outliers over 0.2 € per MWh and km and a comparatively high dispersion. This is caused by the wide range of CAPEX equations for pipelines that are part of this model. At distances overs 100 km the median C_MWh_km of pipelines do not increase because - in contrast to the trucks - the pipeline costs do not decrease with higher distance as a recompression station is required every 250 km and the pipe costs itself are invariant with distance.

The main messages of figure 7 are: Over a transport distance of over 1000 km CG_trucks require a substantial amount of transport energy per MWh of transported hydrogen (in the form of diesel) with a median of 48.6% because of their low capacity. Secondly, the energy investment for pipelines over high distances of 34.6% make them the second least suitable option for land transport with regards to ConvTransE. The figure shows the transport energy (TransE) expressed as percentage of transported MWh of hydrogen of the modes of land transport in relation to the transport distance.

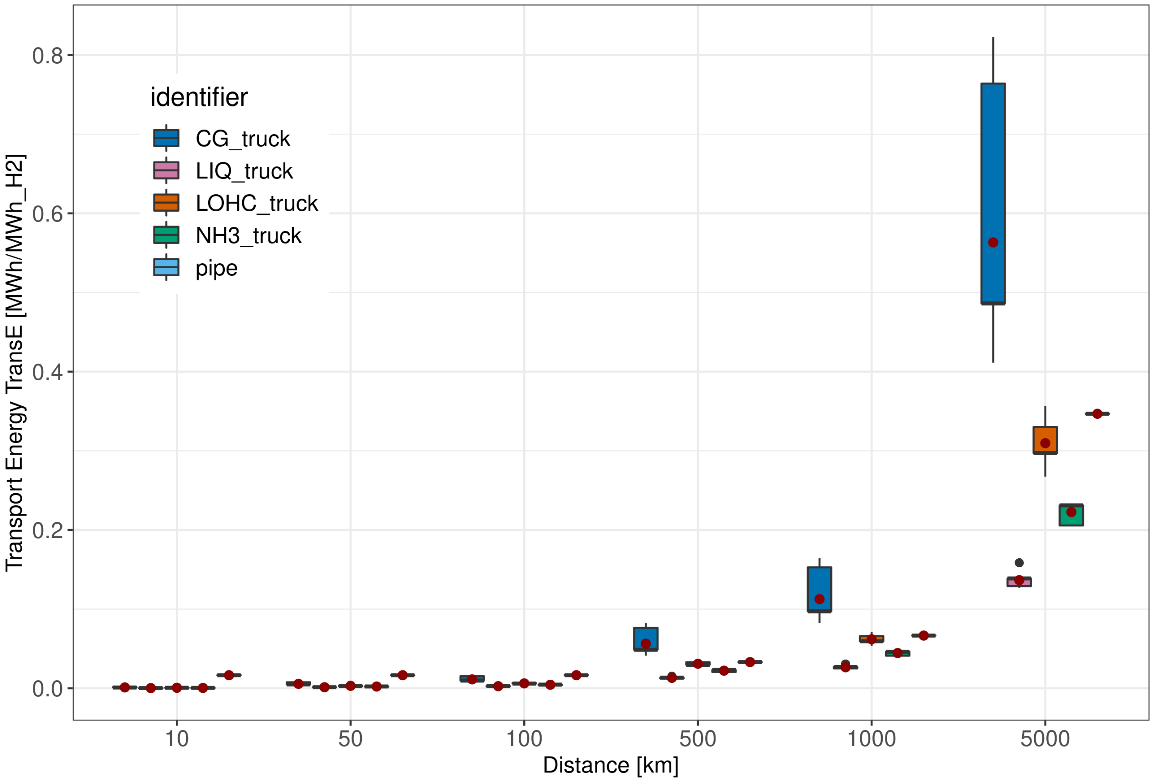


Figure 7: Land: total conversion and transport energy per medium without conversion; the red dot shows the mean

5.2.2 Transport overseas

The three options for transport with ships in this model are liquid hydrogen carriers (LIQ_ship), LOHC tankers (LOHC_ship) and ammonia tankers (NH3_ship). The costs per MWh of transported hydrogen per kilometer (C_MWh_km) without conversions are plotted against transport distance in figure 8. The most important result is that, for all distances and mediums, the costs for sea transport are one order of magnitude lower than the comparable costs for land transport in figure 6. This means that within the limits of this model (that does not regard neither terminals nor storage), independent on the assumption of the used medium ship transport is always more economic than land transport.

It is also worth noting that in regards to C_MWh_km LIQ_ships are much more expensive than LOHC_ships and NH3_ships over all transport distances, NH3_ships being the overall cheapest option. If the conversions are not considered, LIQ_ships are the most expensive option overall. Still, the CAPEX costs for LIQ_ships could not be based on already existing ships but are based on design studies so the real C_MWh_km could deviate. CAPEX costs for NH3_ship and

LOHC_ship on the other hand were based on already existing markets, see chapter 4.7.

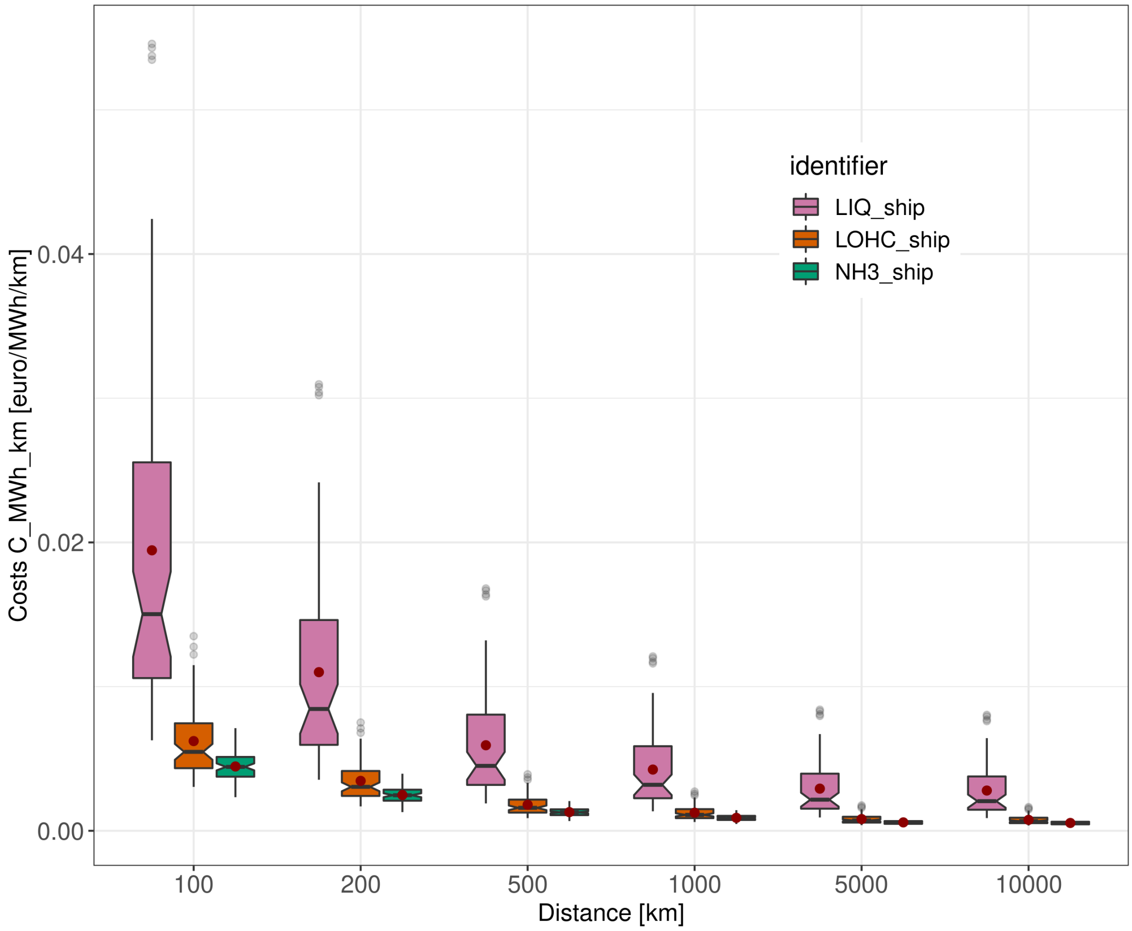


Figure 8: Sea: total transport costs per medium C_MWh/km without conversion

5.3 Final costs of pathways

If conversions and modes of transport are only analysed separately, it is impossible to determine the best option for hydrogen transport as the results of transport and conversion cost analyses are not congruent. For example, NH3_ships are the cheapest option for transport overseas, but NH3_Conv_aC is the most expensive conversion. Therefore, pathways are an essential component of the understanding of hydrogen transport. As outlined in chapter 3.1, pathways include one mode of transport and all conversions necessary for this mode of transport. The notation for pathways is for example: p_CG_truck_aC, which stands for pathway (p) of CG_truck with all conversions necessary (aC).

5.3.1 Pathways for the transport on land

Figure 9 shows the final costs for hydrogen at an hydrogen generation price of 60 €/MWh for all pathways on land in €/MWh. As explained in 3.1, final costs include generation, conversion, transport and loss of hydrogen. The boxplots contain the conversion costs for all plant sizes from 365 tons/year to 180,000 tons/year, hence the broad cost ranges and the outliers. The greatest difference in comparison to figure 6 that does not include conversions is that NH3_truck is now the most expensive or second most expensive transport option. This is because of the high conversion costs but also because of a loss of 17.8% for the whole pathway. CG_trucks on the other hand are competitive for short transport distances but become the most expensive based on median costs at 5000 km. This is solely because of the transport, as the compression is very cheap in comparison and the loss that occurs during p_CG_truck_aC is only at 0.5%. The most economic pathways are p_pipe_aC and p_LIQ_truck_aC. The loss during p_LIQ_truck_aC amounts to 5.4% at the 5000 km, primarily because of boil-off during the transport but also due to loss during the liquefaction (which accounts for around 1.6%).

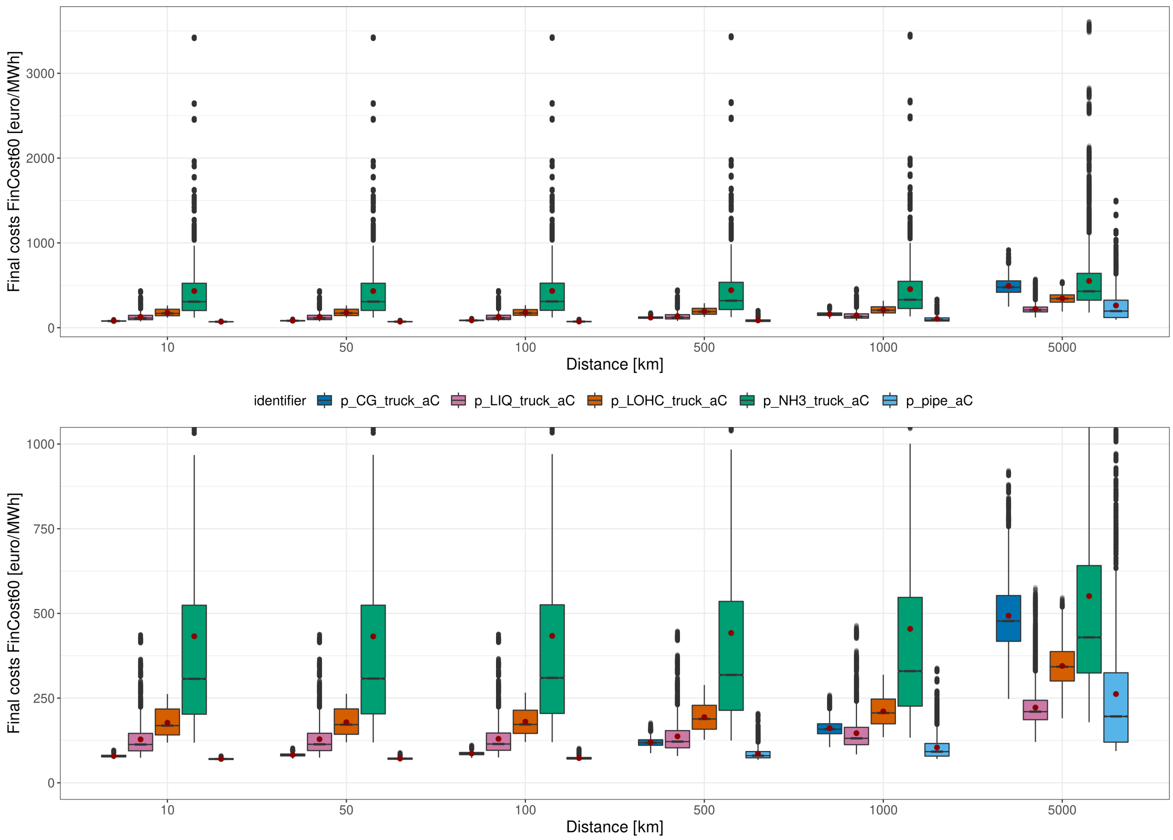


Figure 9: Land: Final costs for generation, conversion, transport (FinCost60) - the two plots only differ in the y-axis range; the upper plot shows the full range with all outliers, the lower plot zooms into a smaller cost range; the red dot shows the mean

The energy required for conversion and transport ConvTransE is plotted against the transport distance for all pathways on land in figure 10. The pathways p_LOHC_truck_aC and p_NH3_truck_aC have high ConvTransE of around 30 to 40% even for short distances and a median ConvTransE of 58.6% and 67.3% respectively for the longest distance; the high energy demand mainly stems from the conversions. p_CG_truck_aC has the second lowest ConvTransE for short distances but due to the small capacity of CG_trucks, the ConvTransE rises to a median of 58% for 5000 km transport distance. p_LIQ_truck_aC and p_pipe_aC have the

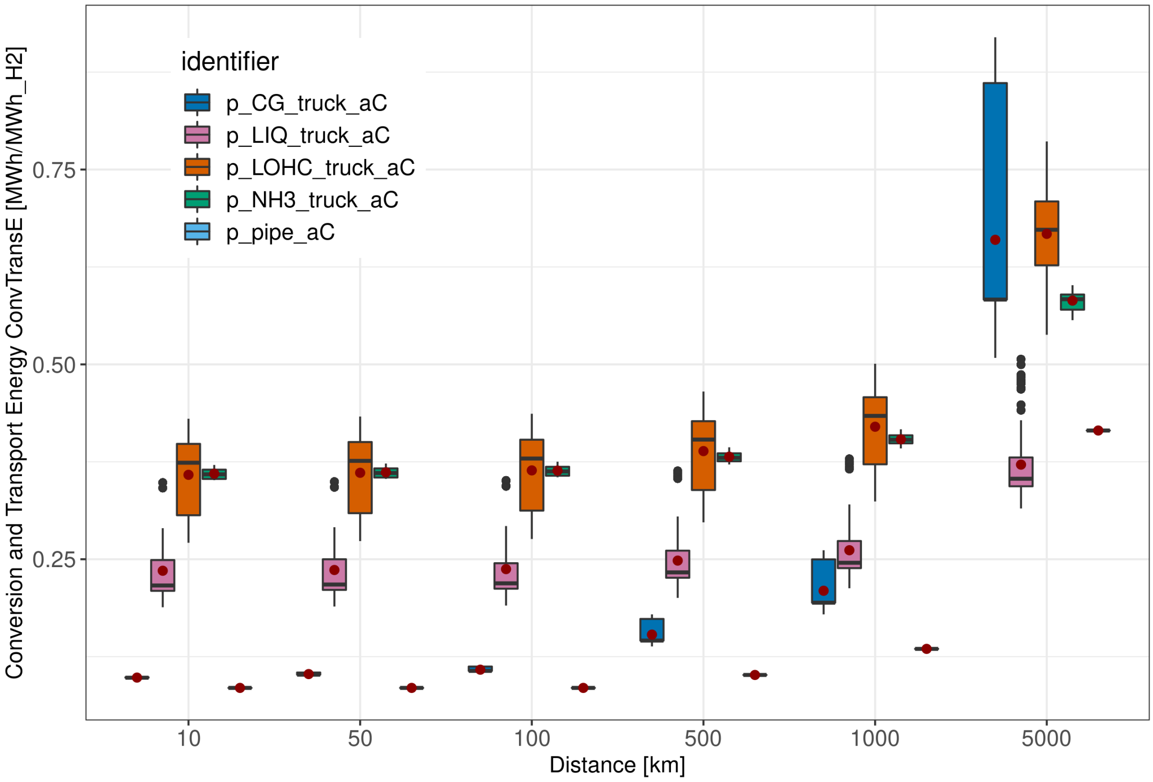


Figure 10: Land: total conversion and transport energy per medium with conversion; the red dot shows the mean

lowest ConvTransE for a 5000 km transport distance with a median of 35% for p_LIQ_truck_aC and 41.5% for p_pipe_aC. For very short transport distances, p_CG_truck_aC is the best option based on ConvTransE with a median around 8%.

5.3.2 Pathways for the transport overseas

The inclusion of conversions into the sea transport completely changes the conclusion on the most economic option for ship transport. Figure 11 displays the final costs for generation, conversion and transport at an hydrogen generation price of 60 € (FinCost60). As the quantity of hydrogen Q is responsible for the highest variance, FinCost60 is plotted against Q and not against the transport distance. The median at FinCost60 of p_NH3_ship_aC is significantly higher than the median of all other pathways, even at very high Q. Overall, p_LIQ_ship_aC are the cheapest pathways for sea transport. This holds true although LIQ_ships are the only ships with considerable boil-off. Even at the highest transport distances and highest Q, the loss due to boil-off and conversion is only 4.6%, substantially more compared to the roughly 1% loss for p_LOHC_ship_aC but still less than the 17.8% lost in p_NH3_ship_aC.

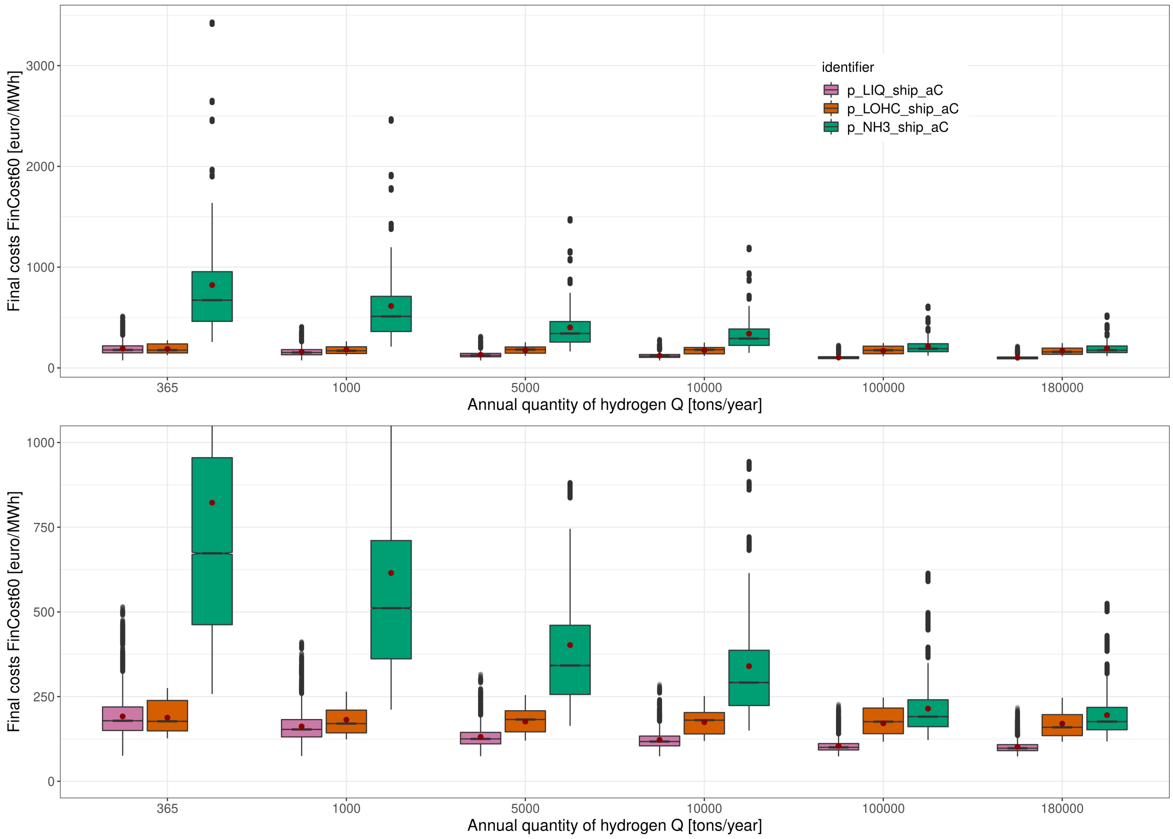


Figure 11: Sea: Final costs for generation, conversion, transport (FinCost60) - the two plots only differ in the y-axis range; the upper plot shows the full range with all outliers, the lower plot zooms into a smaller cost range; the red dot shows the mean

Plot 12 shows ConvTransE in MWh/MWh_H2 for ship transport pathways against distance. The high dispersion of p_LIQ_ship_aC does not stem from variability in the conversion efficiency but in the transport part of the pathway due to the capacity of the ship. Transport energy TransE is influenced by two main factors which are the capacity and the consumption as TransE is measured in MWh/MWh_H2. One of the LIQ_ships has a very low capacity but does not assume a lower consumption, therefore the range of TransE is very high. This is linked to the overall uncertainty regarding LIQ_ships. Notwithstanding, the conversion energy ConvE is much lower for Liq_Conv_aC than for LOHC_Conv_aC and NH3_Conv_aC (see figure 5) and the ship consumption during transport is roughly comparable. Therefore, it can be argued that overall p_LIQ_ship_aC has a lower median ConvTransE than p_NH3_ship_aC and p_LOHC_ship_aC and p_LOHC_ship_aC has the highest median ConvTransE for all distances, which is what the plot shows.

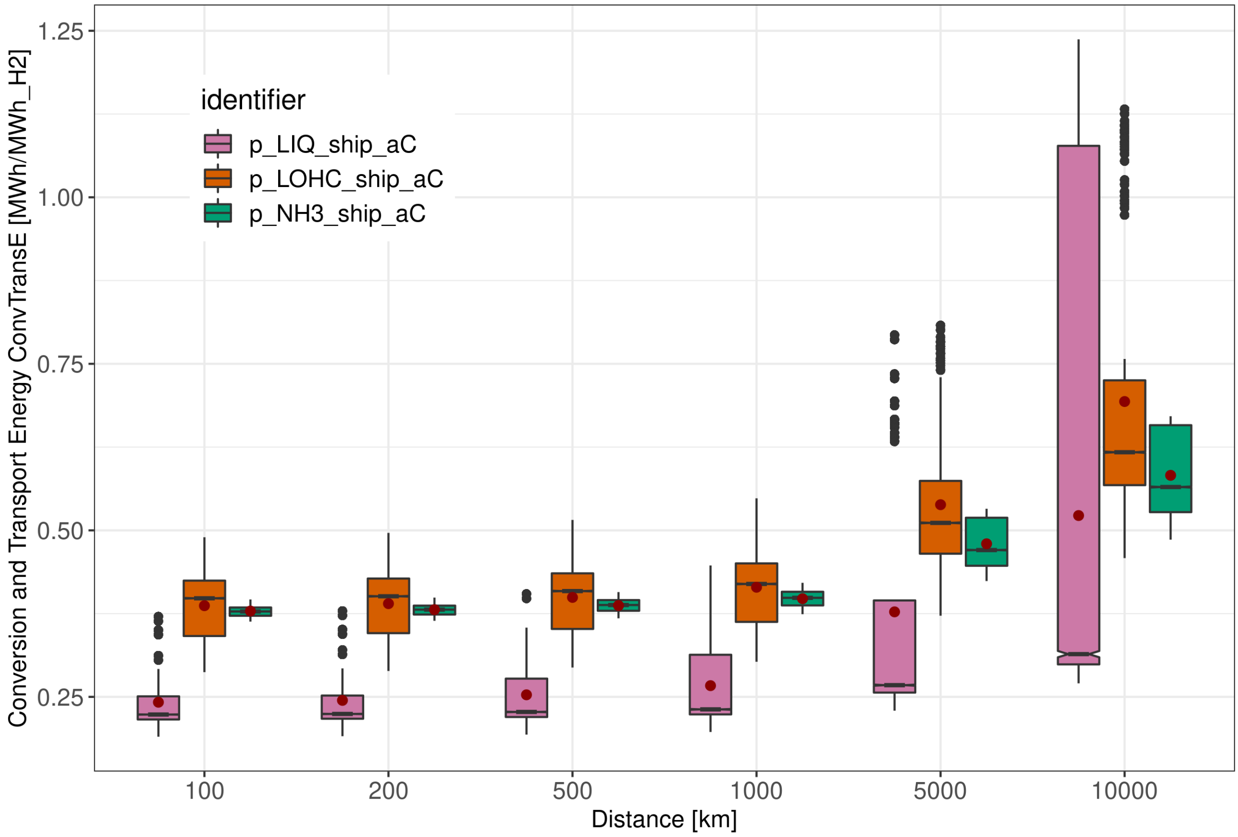


Figure 12: Sea: total conversion and transport energy per medium with conversion; the red dot shows the mean

5.4 Combined pathways

For the compilation of combined pathways the best pathways based on final costs and ConvTransE are selected. For transport overseas, these are p_LIQ_ship_aC and p_LOHC_ship_aC, for land transport p_pipe_aC and p_LIQ_truck_aC. These were combined into the combined pathways p_LIQ_ship_LIQ_truck_aC, transport of liquid hydrogen by ship and truck, p_LIQ_ship_pipe_aC, which combines liquid hydrogen carriers with pipeline transport, and p_LOHC_ship_pipe_aC, the combination of LOHC tankers with pipeline transport. p_LOHC_ship_LIQ_truck_aC was not included as it would include two costly and energy intensive conversions.

Figure 13 shows the FinCost60 of all three combined pathways plotted against the distance on land. Before plotting, the combined pathways were fixed to a distance on sea of 5000 km. The boxplots contain the conversion costs for all Q. For all transport distances on land, the order of the combined pathways with respec to FinCost60 is: p_LIQ_ship_LIQ_truck_aC < p_LIQ_ship_pipe_aC < p_LOHC_ship_pipe_aC. This holds true for all Q except Q=365 tons/year and for all transport distances on sea (not shown as plots here).

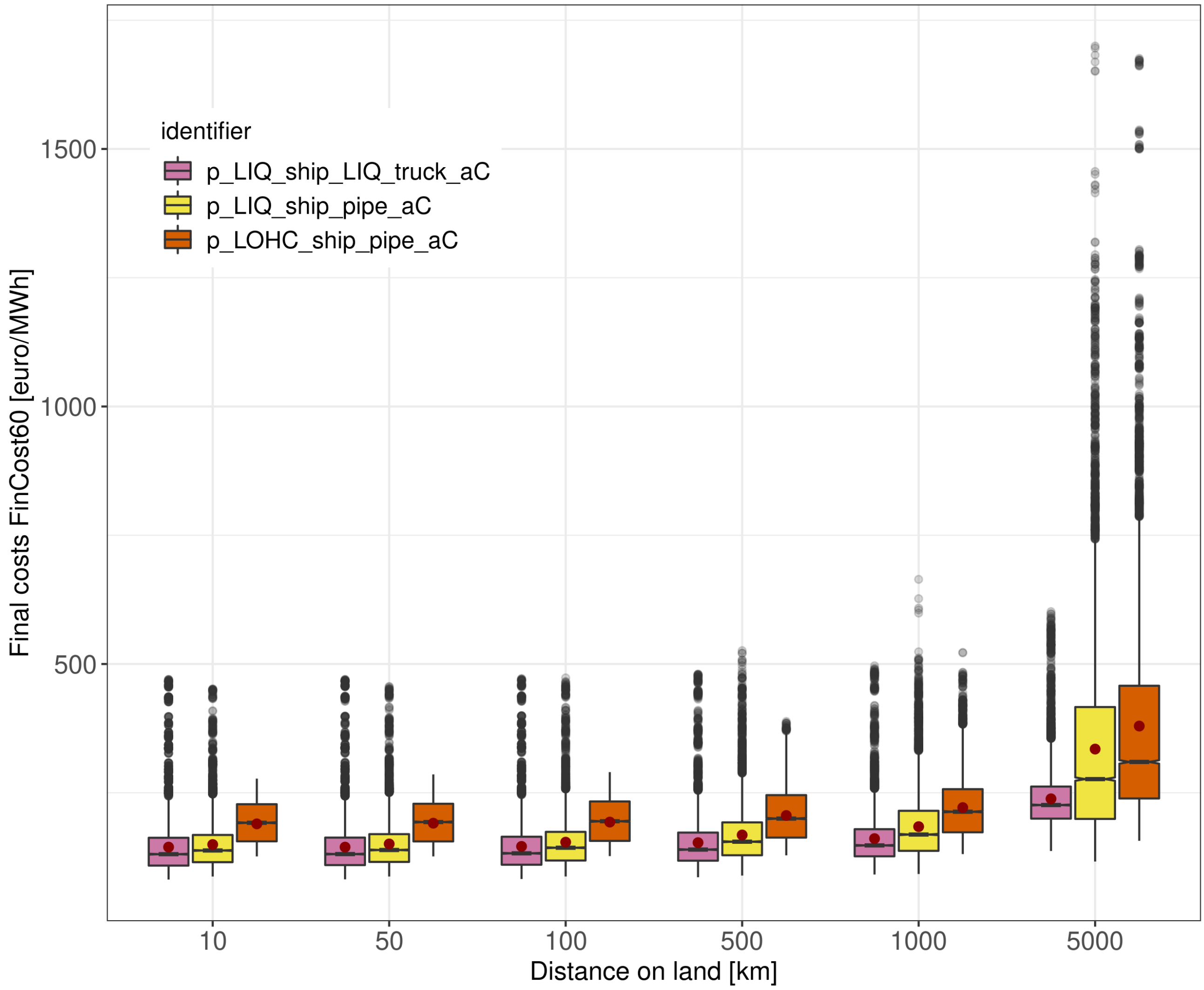


Figure 13: Combined Pathways: Final costs per medium for generation, conversion, transport (FinCost60); the red dot shows the mean

ConvTransE paints a similar picture. Figure 14 displays the ConvTransE of the three combined pathways against the distance on land. As with figure 13, the order of the combined pathways in regards to ConvTransE is again: p_LIQ_ship_LIQ_truck_aC < p_LIQ_ship_pipe_aC < p_LOHC_ship_pipe_aC. This is true for all distances on sea and Q (not plotted here). Both plots have a lot of outliers for all combined pathways. This is because they are a product of three to four joins and every join increases the dispersion and uncertainty. The results should thus be interpreted more as a general guideline and do not fully allow for exact cost estimations.

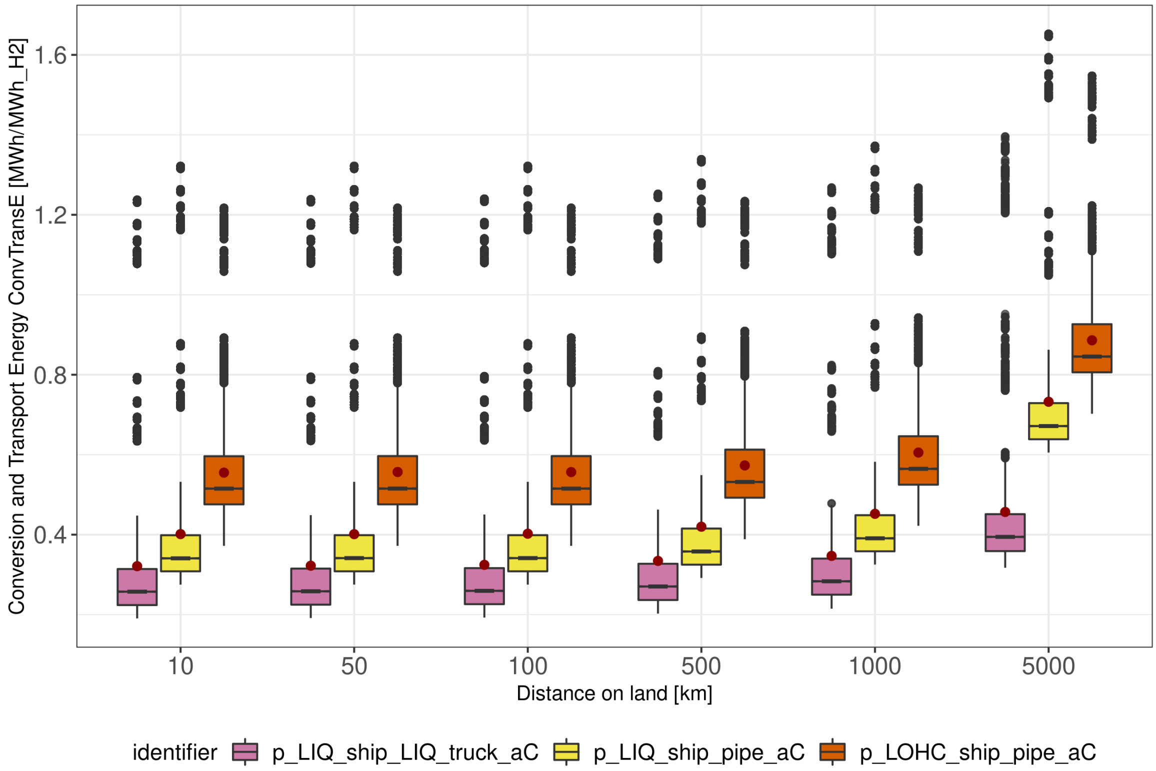


Figure 14: Combined Pathways: conversion and transport energy; the red dot shows the mean

5.5 Standardized regression

For further hydrogen infrastructure design, it is valuable to know which factors influence the C_MWh of the pathways the most. One answer to this question can be found by performing a regression over the factors that influence the C_MWh. As explained in chapter 3.1, a standardized regression using standardized/ beta coefficients is chosen. For this purpose, the predefined inputs (such as electricity cost or quantity of hydrogen Q) were set to a much higher range, see table 13 in the appendix.

Table 14 lists the beta coefficients for all modes of transport and conversions. The first column contains all modes of transports/ conversion steps, every row is one regression result - the dependent variable C_MWh is explained by the independent variables in all other columns using the dataset identified in the first column. The regressions were performed in advance of all joins using the output tables. All coefficients are significant to the 0.05 threshold, the ones that were not significant are marked in grey. ”ECuse” and ”ECuse2” stand for energy carrier use/ consumption, in the case of LOHC_Conv_dehyd, two energy carriers (electricity and gas) are used. The kind of energy carrier used varies with each row. The cost of the energy carrier can be found in the columns ”diesel”, ”HFO” (heavy fuel oil), ”electricity” and ”gas” (natural gas); they give the standardized coefficient for the energy carrier price in the column. ”DriverW” stands for the driver’s wage, it was only implemented for the trucks.

For all modes of transport, the transport distance has the highest influence on C_MWh. For trucks, an increase of one standard deviation in the distance boosts C_MWh by roughly 0.95 standard deviations. The second most influential variable for truck transport is the driver's wage. Diesel costs, CAPEX costs and the capacity have roughly equal influence on C_MWh. The ECuse is blank for all trucks and the compressions as it was implemented without any variance (a constant). The regression coefficients should be interpreted with caution. In the case of the truck capacity for example, the capacity of CG_trucks has a higher influence on C_MWh than for the other trucks. This is because the capacity of CG_trucks was implemented with a higher range and not because the capacity of the other trucks is somehow less important. The coefficients can be compared within one row (intra) but not between rows (inter). Although LIQ_trucks and LIQ_ships have boil-off and thus loss, the loss column is blank for these modes of transport as the boil-off was implemented as a constant in relation to the transport distance.

In the case of pipelines, CAPEX and the diameter of the pipe have the second and third most influence on C_MWh. If the standard deviation of the pipe diameter increases by one, C_MWh decrease by 0.25 standard deviations. Thus, the bigger the diameter, the cheaper the pipeline transport.

The C_MWh of ships is heavily influenced by the capacity, the interest rate and the CAPEX and much less by the HFO costs. The CAPEX is negative for NH3_ships which is an odd behaviour. This effect occurs because CAPEX, capacity and ECuse were implemented specific to ship types and are therefore linked. A high CAPEX therefore coincides with a much higher capacity which results in a lower C_MWh and a negative coefficient.

The coefficients with the highest absolute value for conversions are on the whole CAPEX, capacity and Q. This points towards a huge influence of economies of scale. For conversions with overall lower CAPEX such as the compression, the electricity costs have a high influence on C_MWh. The coefficient of capacity is negative for all conversions except compression, meaning that a higher capacity lowers C_MWh. For the compressions, CAPEX was linked to capacity (in this case base power in kW), which is the same effect as with NH3_ship. Some of the conversion results have to be interpreted with caution as some parameters have a narrow range due to data availability. The interest rate (”interest”) is significant for all modes of transport and mediums.

6 Discussion

The results clearly favor liquid hydrogen pathways. The combined pathways associated with the least final costs and the least ConvTransE both include LIQ_ships - a promising result as there is no trade-off between costs and ConvTransE. All results discussed in this section include, if not specifically stated otherwise, all conversions necessary for the pathway; for better readibility the aC was omitted.

Regarding ship transport, LIQ_ships are preferable over other ship types in terms of costs and ConvTransE. If one can choose between land or sea transport, pipelines were found to be the best option up until a transport distance of 1000 km. At 500 km, the costs per MWh of hydrogen (C_MWh) are 19.1 €/MWh or 0.64 €/kgH2 and 10.1% ConvTransE. At transport distances over

1000 km, LIQ_ships become the best option globally with a median of 65 €/MWh (C_MWh) or 2.15 €/kgH2 at 5000 km and 22.7% ConvTransE.

Pipelines require huge upfront investments for the pipeline installation and high hydrogen throughput to be profitable; this could slow down or even impede the transition to hydrogen [compare 83, p.18130]. For the transition period or if the pipeline investment is not an option, LIQ_trucks are therefore the best alternative to pipelines for land transport. They do not depend on a high throughput (the smallest unit being one truck load of liquid hydrogen), have smaller initial investment costs (of one truck minimum) and the liquefaction and evaporation plants can be used for LIQ_ship transport as well. Furthermore, the combined pathway p_LIQ_ship_LIQ_truck is the cheapest option and has the lowest ConvTransE. If a combination of sea and land transport is required p_LIQ_ship_LIQ_truck is thus the preferable option according to this analysis. For short-distance transport of up to 100 km on land, CG_trucks are the cheapest truck transport option and only slightly more expensive than pipelines. At a transport distance of 100 km C_MWh are at 25.7 €/MWh or 0.85 €/kgH2 and the ConvTransE amounts to 10.6%.

LOHC - based pathways are more expensive and have higher ConvTransE than all other LIQ pathways, pipeline transport and CG_trucks at short distances. The conversion into and out of the medium requires the highest amount of energy of around 37%. The favorable chemical properties of LOHC and the lower CAPEX costs for trucks and ships do not make up for the high costs and high ConvTransE in the conversion. Yet, this study does not consider long-term or seasonal storage. As proponents of LOHC-based pathways argue, compressed gas and liquid hydrogen are unsuitable for long-term storage because of their high volume and boil-off. LOHCs are much easier to store and could therefore be used in seasonal storages or for decentralized small-scale systems [1, 84, 83, 96].

NH3 - based pathways on the other hand are unmistakably ruled out for hydrogen transport. They are across the board more expensive and more energy intensive than all other mediums. Ammonia also does not have more favourable chemical or physical properties than the other mediums and is the most toxic (compare chapter 4.4). The main obstacle for ammonia pathways is the complex, multi-step conversion process. In a possible niche-application of ammonia as fuel in e.g. ammonia fuel cells [52], a case could be made for ammonia transport as the dehydrogenation process at the end of the transport chain could be avoided. If that was the case, other factors such as the possible end-use of ammonia as ”green fertilizer” would further complicate the picture. This is not within the scope of this study and is thus not further discussed here.

It is important to note that the cost figures presented in the result section include the whole range of predefined variables, i.e. all values assumed for the interest rate, diesel cost, electricity cost etc. (see chapter 3.3.1). This has an effect on the figures as it expands the boxplots. All possible combinations of predefined variables are included in one boxplots, hence also the combination of the highest value of every variable. This results in more expensive outliers and in a larger range.

6.1 Comparison with other studies

Studies similar to the one presented here vary greatly in scope, system boundaries (with/ without hydrogen generation or storage), data, time horizon and assumptions. Hence, it is difficult to compare the results in terms of exact costs or energy demands. A more fruitful approach is the focus on a comparable order of magnitude of costs and energy demands and more importantly on the ranking of modes of transport and mediums.

Studies on land transport of hydrogen, especially those on truck transport, are congruent with the results of this thesis. This is expected, as the model design is partially drawn from these very studies and the data also features in this study. Still, they are not replica, as data and model assumptions were taken from a much higher range of sources.
Reuß et al. conclude that for demand below 20 tons/day and distances of up to 100 km, CG_truck delivery is the best option and LIQ_truck becomes cost-efficient for distances over 500 km [67]. In a subsequent later publication, Reuß et al. argue for a combination of pipeline transmission and CG_trucks for distribution or short distance transport. "The most beneficial hydrogen supply chain in terms of the three investigated scenarios was salt cavern storage, in combination with pipeline transmission and GH2 trailer distribution."[68, p.449].
Yang and Ogden come to a very similar conclusion, with the addition of LIQ_trucks for medium amounts of hydrogen and long distances [98]. This is congruent with André et al., who state that "for the mid term perspective and low market share, the trucks are the most economical options" [9, p.10323] - in this study "trucks" refers to CG_trucks and LIQ_trucks. It is also in agreement with Moradi and Groth who conclude: "[The transportation of liquid hydrogen] is considered to be economical for high demands (above 500 kg/day) and mid range distances" [53, p. 12259].
Demir and Dincer analyse three transport and storage scenarios. The most environmentally friendly and cost effective scenario is scenario three that features a large scale pipeline network. Notwithstanding, their delivery costs of 2.73 $/kg H_2 for a 100 km delivery is considerably higher than the 0.38 €/kg H_2 found here for the same distance. This is because the study also includes storage [21].

As pipelines feature so prominently as the best option for long-distance, high volume land transport some further remarks on their design: Firstly, the diameter of the pipeline has been set to 100 to 300 mm in this model. This results in a quantity of hydrogen of about 160 000 tons/year, which roughly corresponds to the highest Q assumed for the conversions and fits to the diameter range of most studies included for the pipeline calculation. Still, a wider diameter is possible. Moreno-Benito, Agnolucci, and Papageorgiou include pipeline diameters of up to 600 mm [54], Johnson and Ogden mention diameters of 900 mm [40] and Heuser et al. even go over 1m [36]. A diameter of 1 m would result in an hydrogen throughput of 1,772,173 tons/year or about 4855 tons/day, which is unrealistic for now and the nearer future. Still, wider diameters are possible and would decrease the costs significantly. Furthermore, the pipeline length is limited by ConvTransE. As figure 10 shows, ConvTransE (i.e. conversion and transport energy, in this case mainly the energy needed for the compressors) rises with longer distances because of the need for recompression. At 5000 km ConvTransE is already at 41.5%. This is still the second lowest ConvTransE for land transport at this distance. Nevertheless, ConvTransE is bound to rise with even longer transport distances. Thirdly, there are developments for fibre-reinforced polymer pipelines that could lower the installation and thus CAPEX costs of pipelines considerably [87]. This new technology could unfortunately not be included in the model as no reliable data could be acquired, yet it further corroborates the notion of a high future potential for pipeline transport.

Publications that include ship transport and land transport are much more scarce than the ones focusing on land transport alone, apart from the IEA's publication "The Future of Hydrogen" [85], that can be criticized for their optimistic cost assumptions (see chapter 2). Teichmann, Arlt, and Wasserscheid compare LOHC and LIQ pathways for truck transport and ship. They conclude that LOHC_ships have lower transport costs, which is mainly due to the low capacity of the LIQ_ship. More recent studies assume a LIQ_ship with a ten times higher capacity [83].
In an extensive recent study, Ishimoto et al. compare NH3- and LIQ- pathways for hydrogen transport from Norway to Europe and Japan in terms of CO_2-emissions, energy efficiency and levelized cost of energy [39]. They find that in all three categories LIQ-pathways are preferable over NH3-pathways, which is consistent with the results of this study. In contrast, Gallardo et al., who analyse a case study for the transport of hydrogen from Chile to Japan, conclude that NH3_ship transport is slightly cheaper than LIQ_ship transport [31]. This is due to the specific scenario configurations and because their assumptions for the NH3-conversions are more optimistic.

These conflicting results highlight two aspects. Firstly, the need for further research, as the existing studies that combine ship and land transport have conflicting results. Secondly, the importance of including a range of possible values as inputs in the model and not relying on single-value estimations for all calculations. Chapter 5.5 has highlighted the influence of some crucial parameters such as CAPEX and capacity on C_MWh. If only one value is taken for these parameters, it can distort the result, especially in this early phase of a possible hydrogen transport network in which uncertainties are still high. This study addresses this complexity by including a range of values for all input parameters where possible, which also includes global parameters such as the interest rate.

In conclusion, this study was able to replicate previous findings that a combination of CG_trucks for delivery and pipelines for long-distance transport with a possible inclusion of LIQ_trucks is the best form of land transport of hydrogen. The competitiveness of this transport mode has further been shown to be robust to a wide range of inputs and in combination with ship transport (LIQ_ship), which is a new finding. For now, studies are inconsistent in the choice of medium for the cheapest ship transport options. In contrast to land transport, research on ship transport has only begun in recent years. This study is a contribution to that research and clearly points towards LIQ_ships as the cheapest and least energy intensive method.

6.2 Limitations of the model

The model and thus its results are limited by several factors that are rooted in the data quality and in the model design.
The data quality varies considerably between technologies. In cases such as NH3_ships, the technology is already well established and reliable estimations can be made. In other cases including LIQ_ships, there are only design studies so that crucial parameters can only be guesstimated. Furthermore, all prices are adjusted to 2015 € (see chapter 3.2). Often, the base year is not explicitly mentioned in a publication, in that case the year of the publication was taken as the base year; this is noted in the data collection tables. As costs are adjusted to 2015 € based on the base year, an inaccurate assumption can create uncertainty in the results.

The model itself has four main limitations. Firstly, hydrogen storage and ship terminals are not part of the calculations. As explained above, this is due to the very poor data availability and the system boundaries. Still, both factors could potentially alter the result. The second limitation is that the model is based on the premise that a constant supply and demand of hydrogen exists, this is linked to the storage issue. A reliable and steady supply is difficult to achieve with renewable energy resources, as photovoltaic and wind power are characterised by high variability in energy production. A more realistic supply driven model would have to include a variable supply of hydrogen. Another option would be to include massive storage that puffer seasonal changes for all mediums. This would affect the results if the storage options differ significantly in terms of costs and energy efficiency. Thirdly, the model does not consider total costs of transport but only one relevant fraction of the costs. For instance, in road transport it takes the entire road infrastructure for granted and does not factor in road erosion. Other external costs, such as the cost associated to the CO_2 -emissions due to the usage of diesel, HFO and natural gas, are also not part of the model. However, energy efficiency is considered. Fourth, the model in its current implementation outlined in chapter 3.1 takes a long time to compute as it loops over all inputs. Hence, it cannot be extended ad libitum without making the computing time unreasonably long.

Future research should focus on the inclusion of storage options both for long-term and short-term storage and factor in terminals. Furthermore, an inclusion of train transport as another form of land transport would be interesting. Cryogenic freight trains for liquid hydrogen could make a higher capacity LIQ land transport possible which could be a competing technology to pipeline transport, especially in combination with LIQ_ships. Moreover, the adaptation of the model into a supply and demand driven model with variable throughput would make the results more realistic, though much more complicated in the implementation. Beyond that a comparison between hydrogen with other potential renewable energy carriers and with electricity in regards to transport costs and energy efficiencies would be valuable.

7 Conclusion

This study assesses costs, energy efficiencies and conversion and transport energy of state-of-the-art technologies for the long-distance, high-volume transport of hydrogen using a model-based approach. The analysed technologies are compressed hydrogen trucks, liquid hydrogen trucks, ammonia trucks, LOHC trucks, compressed hydrogen pipelines, liquid hydrogen carriers, ammonia carriers and LOHC tankers. The main focus of this study is to identify which mediums are most cost-effective and energy-efficient for land transport, overseas transport and a combination of land and sea transport. For that purpose it includes not only the transport technologies themselves but also all conversion plants that are necessary along the pathway. Furthermore, within the scope of the literature research no other study was found that allowed for more than one value for crucial input parameters so that the variety in input assumptions is reflected in the model.

The established model gives an overview of relevant transport pathways from economic and energy aspects. The results indicate that for high-volume, long-distance land transport, hydrogen pipelines are the optimal choice, for shorter distances and lower volume truck transport can also be a valuable option. For sea transport, liquid hydrogen carriers seem to be the best solution.

At the moment we are at a crucial phase in the design of a possible future hydrogen infrastructure. The findings of this study can aid in the process of deciding for the best transport mediums, so that informed decisions on potentially huge investments for hydrogen infrastructure can be made in the private as well as the public sector. It can also aid in the comparison of hydrogen with other potential renewable energy carriers.

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Eidesstattliche Erklärung

Ich erkläre eidesstattlich, dass ich die Arbeit selbständig angefertigt habe. Es wurden keine anderen als die angegebenen Hilfsmittel benutzt. Die aus fremden Quellen direkt oder indirekt übernommenen Formulierungen und Gedanken sind als solche kenntlich gemacht. Diese schriftliche Arbeit wurde noch an keiner Stelle vorgelegt.

Appendix

Table 13: Data summary for predefined variables long format

parameter	values	unit
H2 generation price	30/50/60/80	euro/MWh
diameter of pipeline	from 100 to 300 by 20	mm
distance (L)	10/20/30/50/100/200/300/400/500/600/700/800/900/1000/2000/3000/4000/5000	km
distance (L_w)	100/200/500/1000/1500/2000/2500/3000/3500/4000/5000/6000/7000/8000/9000/10000	km
interest rate	0.01/0.02/0.03/0.04/0.05/0.06/0.07/0.08/0.09/0.10/0.11/0.12/0.13/0.14/0.15	-
diesel cost	0.5/0.6/0.7/0.8/0.9/1.0/1.1/1.2/1.3/1.4/1.5/1.6/1.7/1.8/1.9/2.0	euro/liter
heavy fuel oil cost	350/360/370/380/390/400/410/420/430/440/450/460/470/480/490/500/510/520/530/540/550	euro/ton
electricity	0.055/0.060/0.065/0.070/0.075/0.080/0.085/0.090/0.095/0.1	euro/kWh
natural gas cost	0.015/0.016/0.017/0.018/0.019/0.020/0.021/0.022/0.023	euro/kWh
Quantity of hydrogen Q	0.365/0.5/0.8/1/2/3/5/10/20/30/40/50/60/70/80/90/100/110/120/130/140/150/160/170/180	ktons/year

Table 14: Standardized coefficients from the standardized regression

identifier	distance	interest	diesel	HFO	electricity	gas	Q	diameter	CAPEX	Capacity	ECuse	ECuse2	DriverW	Loss
CG_truck	0.95	0.06	0.05						0.13	-0.2			0.11	
LIQ_truck	0.96	0.05	0.05						0.06	-0.05			0.12	
LOHC_truck	0.96	0.02	0.06						0.01	-0.08			0.15	
NH3_truck	0.96	0.02	0.07						0.03	-0.04			0.15	
pipe	0.44	0.13			0.01			-0.25	0.3					0.17
LIQ_ship	0.63	0.24		0.01					0.15	-0.68				
LOHC_ship	0.82	0.18		0.08					0.2	-0.36	0.23			
NH3_ship	0.93	0.22		0.09					-0.12	-0.09	-0.04			
Comp_100		0.27			0.62		-0.44		0.71	0.55				
Comp_500		0.29			0.53		-0.48		0.76	0.59				
LIQ_Conv_liq		0.2			0.08		-0.5		0.98	-0.58	0.09			
LIQ_Conv_eva		0.04			0.58		-0.12		0.88	-0.7	0.74			
LOHC_Conv_hyd		0.99			0.004		-0.06		0.003		0.02			0.03
LOHC_Conv_dehyd		0.3			0.06	0.34	-0.52		-0.2		0.3	0.22		0.01
NH3_Conv_hyd		0.26			0.001		-0.4		0.74	-0.39	0.0014			
NH3_Conv_dehyd		0.35			0.21		-0.63							

Table 15: BaseCost and BaseCapacity (in H2) for all conversions

Technology	**CapacityH2**	**unit**	**BaseCost**	**Invest/CapacityH2**
Compressor	4000	kW	1548.5	0.4
Compressor	4000	kW	1164	0.3
Compressor	4000	kW	1548.5	0.4
Compressor	500	kW	4108.8	8.2
Liquefier	712.3287671	tH2/d	1486719787.5	2087125.9
Liquefier	50	tH2/d	112549800.8	2250996
Liquefier	30	tH2/d	63339110.3	2111303.7
Liquefier	50	tH2/d	119426270.8	2388525.4
Liquefier	326.4	tH2/d	300688821.8	921228
Liquefier	50	tH2/d	102981561.4	2059631.2
Liquefier	200	tH2/d	8896331.7	44481.7
Liquefier	50	tH2/d	99601593.6	1992031.9
Evaporator	1	tH2/d	2845.8	2845.8
Evaporator	1	tH2/d	5884.7	5884.7
Evaporator	6	tH2/d	135946.3	22657.7
Evaporator	1.56	tH2/d	28778.4	18447.7
Evaporator	1	tH2/d	5691.5	5691.5
LOHC_hyd	144	tH2/d	24641447.7	171121.2
LOHC_hyd	300	tH2/d	37943464.2	126478.2
LOHC_dehyd	0.648	tH2/d	726826.5	1121645.8
LOHC_dehyd	300	tH2/d	28457598.2	94858.7
NH3_hyd	609.116	t H2/d	4395023183.2	7215412.5
NH3_hyd	755.432	t H2/d	5142554168.5	6807434.9
NH3_hyd	80.99	t H2/d	2680292019.6	33094110.6
NH3_hyd	1.246	t H2/d	106555951.9	85518420.4
NH3_hyd	1.246	t H2/d	37704413.7	30260364.2
NH3_hyd	1.246	t H2/d	52458314.8	42101376.2
NH3_hyd	58.918	t H2/d	1229491752.1	20867846
NH3_hyd	332.148	t H2/d	9752328577.8	29361394.9
NH3_hyd	35.956	t H2/d	839333036.1	23343337.3
NH3_hyd	87.22	t H2/d	899987962.6	10318596.2
NH3_hyd	0.89	t H2/d	19671868	22103222.5
NH3_hyd	0.89	t H2/d	14753901	16577416.9
NH3_hyd	46.814	t H2/d	1096706642.9	23426894.6
NH3_hyd	46.814	t H2/d	1106542576.9	23637001.3
NH3_hyd	131.008	t H2/d	621303165.4	4742482.6
NH3_hyd	68.352	t H2/d	347536335.3	5084508.7
NH3_hyd	2.492	t H2/d	32786446.7	13156680.1
NH3_hyd	181.916	t H2/d	824579135.1	4532746.6
NH3_hyd	1.78	t H2/d	36065091.4	20261287.3
NH3_ASU	4.272	t H2/d	33496967.9	7841050.5
NH3_ASU	4.272	t H2/d	37625689.3	8807511.5
NH3_HB	4.272	t H2/d	69304071.6	16222863.2
NH3_HB	4.272	t H2/d	116769380.5	27333656.5
NH3_dehyd	731.5	t H2/d	488493644.5	667790.9

Table 16: Result summary for total conversion costs per medium (C_MWh)

Q	identifier	median	mean	min	max
365	Comp_100	9.6434	9.7522	5.9353	15.3063
365	Comp_500	14.9074	15.3771	9.0769	24.7714
365	LIQ_Conv_aC	109.5354	121.0465	13.7107	374.033
365	LOHC_Conv_aC	119.8168	124.1488	66.3993	196.3233
365	NH3_Conv_aC	598.5033	746.8709	184.271	3353.0637
1000	Comp_100	8.9998	9.0544	5.6381	13.923
1000	Comp_500	13.941	14.1343	8.5476	22.3076
1000	LIQ_Conv_aC	83.7293	91.2557	13.0545	275.083
1000	LOHC_Conv_aC	114.3619	118.4345	63.0805	187.3431
1000	NH3_Conv_aC	436.0927	540.001	138.0271	2392.8496
5000	Comp_100	8.1208	8.1696	5.2613	12.1688
5000	Comp_500	12.4532	12.5582	7.8764	19.1832
5000	LIQ_Conv_aC	56.4715	60.6474	12.3803	173.4176
5000	LOHC_Conv_aC	108.737	112.5423	59.6583	178.0831
5000	NH3_Conv_aC	266.9957	326.6871	90.3426	1402.7244
10000	Comp_100	7.92	7.8599	5.1294	11.5549
10000	Comp_500	11.7886	12.0066	7.6415	18.0896
10000	LIQ_Conv_aC	48.7035	51.8553	12.1866	144.2148
10000	LOHC_Conv_aC	107.1157	110.8439	58.6719	175.414
10000	NH3_Conv_aC	217.157	265.202	76.5981	1117.333
100000	Comp_100	7.0408	7.0665	4.7915	9.9821
100000	Comp_500	10.5614	10.5936	7.0397	15.2884
100000	LIQ_Conv_aC	32.4841	33.9637	11.7924	84.7878
100000	LOHC_Conv_aC	103.8036	107.3744	56.6568	169.9613
100000	NH3_Conv_aC	116.3753	139.5945	48.5197	534.3095
180000	Comp_100	6.8642	6.9109	4.7252	9.6736
180000	Comp_500	10.2751	10.3164	6.9216	14.7389
180000	LIQ_Conv_aC	29.9891	31.2474	11.7326	75.7655
180000	LOHC_Conv_aC	103.2984	106.8452	56.3495	169.1298
180000	NH3_Conv_aC	100.8492	120.4383	44.2375	445.3931

Table 17: Result summary for total conversion energy (ConvE) per medium

identifier	median	mean	min	max
Comp_100	0.0684	0.0684	0.0684	0.0684
Comp_500	0.097	0.097	0.097	0.097
LIQ_Conv_aC	0.2184	0.2348	0.1881	0.348
LOHC_Conv_aC	0.3732	0.3578	0.2706	0.4295
NH3_Conv_aC	0.3585	0.3593	0.3511	0.3705

Table 18: Result summary for Land: total transport costs per medium (C_MWh/km) without conversion

distance	identifier	median	mean	min	max
10	CG_truck	0.597	0.6227	0.2763	1.2199
10	LIQ_truck	0.2051	0.2056	0.0938	0.3456
10	LOHC_truck	0.2826	0.286	0.1276	0.4794
10	NH3_truck	0.1774	0.1667	0.0878	0.2526
10	pipe	0.1605	0.1611	0.0993	0.4177
50	CG_truck	0.1839	0.191	0.0837	0.3763
50	LIQ_truck	0.0554	0.0553	0.025	0.0928
50	LOHC_truck	0.0835	0.0841	0.0369	0.1419
50	NH3_truck	0.0545	0.0524	0.027	0.0801
50	pipe	0.0434	0.0553	0.02	0.2855
100	CG_truck	0.1321	0.137	0.0596	0.2709
100	LIQ_truck	0.0366	0.0365	0.0164	0.0612
100	LOHC_truck	0.0586	0.0589	0.0256	0.0997
100	NH3_truck	0.0389	0.0382	0.0194	0.0585
100	pipe	0.03	0.0421	0.0101	0.269
500	CG_truck	0.0907	0.0938	0.0404	0.1865
500	LIQ_truck	0.0216	0.0215	0.0096	0.036
500	LOHC_truck	0.0386	0.0387	0.0165	0.066
500	NH3_truck	0.0268	0.0267	0.0133	0.0412
500	pipe	0.0223	0.0343	0.0041	0.2603
1000	CG_truck	0.0851	0.0884	0.038	0.176
1000	LIQ_truck	0.0197	0.0197	0.0087	0.033
1000	LOHC_truck	0.036	0.0361	0.0154	0.0618
1000	NH3_truck	0.0253	0.0253	0.0125	0.0391
1000	pipe	0.0225	0.0346	0.0041	0.2629
5000	CG_truck	0.0808	0.0841	0.0361	0.1675
5000	LIQ_truck	0.0187	0.0188	0.0083	0.0314
5000	LOHC_truck	0.0339	0.0341	0.0145	0.0584
5000	NH3_truck	0.0241	0.0242	0.0119	0.0374
5000	pipe	0.0242	0.0373	0.0043	0.2846

Table 19: Result summary for Land: total conversion and transport energy (ConvTransE) per medium without conversion

distance	identifier	median	mean	min	max
10	CG_truck	0.001	0.0011	0.0008	0.0016
10	LIQ_truck	0.0003	0.0003	0.0002	0.0003
10	LOHC_truck	0.0006	0.0006	0.0005	0.0007
10	NH3_truck	0.0005	0.0004	0.0004	0.0005
10	pipe	0.0165	0.0165	0.0165	0.0165
50	CG_truck	0.0049	0.0056	0.0041	0.0082
50	LIQ_truck	0.0013	0.0013	0.0012	0.0015
50	LOHC_truck	0.003	0.0031	0.0027	0.0036
50	NH3_truck	0.0023	0.0022	0.0021	0.0023
50	pipe	0.0165	0.0165	0.0165	0.0165
100	CG_truck	0.0097	0.0113	0.0082	0.0165
100	LIQ_truck	0.0027	0.0026	0.0024	0.0031
100	LOHC_truck	0.0059	0.0062	0.0053	0.0071
100	NH3_truck	0.0046	0.0045	0.0041	0.0046
100	pipe	0.0165	0.0165	0.0165	0.0165
500	CG_truck	0.0486	0.0563	0.0411	0.0823
500	LIQ_truck	0.0134	0.0132	0.0123	0.0153
500	LOHC_truck	0.0297	0.031	0.0267	0.0357
500	NH3_truck	0.0231	0.0223	0.0206	0.0231
500	pipe	0.0331	0.0331	0.0331	0.0331
1000	CG_truck	0.0972	0.1126	0.0823	0.1645
1000	LIQ_truck	0.0269	0.0265	0.0247	0.0308
1000	LOHC_truck	0.0594	0.0619	0.0535	0.0713
1000	NH3_truck	0.0462	0.0445	0.0411	0.0462
1000	pipe	0.0666	0.0666	0.0666	0.0666
5000	CG_truck	0.4862	0.5632	0.4114	0.8227
5000	LIQ_truck	0.1388	0.1366	0.127	0.1586
5000	LOHC_truck	0.2971	0.3096	0.2674	0.3565
5000	NH3_truck	0.2311	0.2226	0.2057	0.2311
5000	pipe	0.3468	0.3468	0.3468	0.3468

Table 20: Result summary for Sea: total transport costs per medium (C_MWh/km) without conversion

distance	identifier	median	mean	min	max
100	LIQ_ship	0.015	0.0195	0.0063	0.0546
100	LOHC_ship	0.0055	0.0062	0.003	0.0135
100	NH3_ship	0.0044	0.0045	0.0023	0.0071
200	LIQ_ship	0.0084	0.011	0.0035	0.031
200	LOHC_ship	0.003	0.0035	0.0017	0.0075
200	NH3_ship	0.0025	0.0025	0.0013	0.004
500	LIQ_ship	0.0045	0.0059	0.0019	0.0168
500	LOHC_ship	0.0016	0.0018	0.0009	0.0039
500	NH3_ship	0.0013	0.0013	0.0007	0.0021
1000	LIQ_ship	0.0032	0.0042	0.0014	0.0121
1000	LOHC_ship	0.0011	0.0013	0.0006	0.0027
1000	NH3_ship	0.0009	0.0009	0.0005	0.0014
5000	LIQ_ship	0.0022	0.0029	0.0009	0.0084
5000	LOHC_ship	0.0007	0.0008	0.0004	0.0018
5000	NH3_ship	0.0006	0.0006	0.0003	0.0009
10000	LIQ_ship	0.0021	0.0028	0.0009	0.008
10000	LOHC_ship	0.0007	0.0008	0.0004	0.0016
10000	NH3_ship	0.0005	0.0005	0.0003	0.0009

Table 21: Result summary for Land: Final costs for generation, conversion, transport (FinCost60)

distance	identifier	median	mean	min	max
10	p_CG_truck_aC	78.6321	79.0285	69.9857	97.2722
10	p_LIQ_truck_aC	113.0541	128.1586	73.8422	437.7393
10	p_LOHC_truck_aC	168.8019	177.2758	118.6502	261.7971
10	p_NH3_truck_aC	306.7703	432.4703	118.3155	3428.545
10	p_pipe_aC	70.2869	70.3539	66.3258	80.0908
50	p_CG_truck_aC	81.9264	82.353	71.4087	103.8886
50	p_LIQ_truck_aC	113.6181	128.6783	74.4064	439.0649
50	p_LOHC_truck_aC	171.6421	178.649	119.64	262.6316
50	p_NH3_truck_aC	307.5935	432.0374	118.9856	3429.866
50	p_pipe_aC	71.154	71.5087	66.3313	90.1882
100	p_CG_truck_aC	86.0223	86.5212	73.1875	112.1591
100	p_LIQ_truck_aC	114.5031	129.6159	74.9217	439.0802
100	p_LOHC_truck_aC	172.2589	180.279	120.1471	266.1209
100	p_NH3_truck_aC	309.6893	433.704	119.9896	3431.69
100	p_pipe_aC	72.0304	72.9522	66.3382	102.81
500	p_CG_truck_aC	118.0664	119.6609	87.4176	178.3231
500	p_LIQ_truck_aC	121.5954	136.9896	78.9966	448.8678
500	p_LOHC_truck_aC	188.4042	193.6421	127.0178	288.7607
500	p_NH3_truck_aC	318.4447	442.2395	124.628	3444.916
500	p_pipe_aC	80.0263	86.2118	67.7011	206.3902
1000	p_CG_truck_aC	158.1497	161.1828	105.2053	261.0281
1000	p_LIQ_truck_aC	131.246	146.427	83.8583	464.6246
1000	p_LOHC_truck_aC	206.2026	210.6642	134.7377	318.9461
1000	p_NH3_truck_aC	329.6656	454.2961	133.1409	3464.872
1000	p_pipe_aC	91.9464	104.3248	70.4161	339.7814
5000	p_CG_truck_aC	477.3747	493.1045	247.6245	922.6683
5000	p_LIQ_truck_aC	209.9859	222.0561	120.4521	577.3824
5000	p_LOHC_truck_aC	342.5161	344.9738	190.6025	547.312
5000	p_NH3_truck_aC	429.2439	551.061	178.8454	3612.085
5000	p_pipe_aC	195.9436	262.0965	93.742	1505.73

Table 22: Result summary for Land: total conversion and transport energy (ConvTransE) per medium without conversion

distance	**identifier**	**median**	**mean**	**min**	**max**
10	p_CG_truck_aC	0.098	0.0981	0.0978	0.0987
10	p_LIQ_truck_aC	0.2163	0.2352	0.1884	0.3483
10	p_LOHC_truck_aC	0.3738	0.3583	0.2711	0.4302
10	p_NH3_truck_aC	0.3589	0.3597	0.3515	0.371
10	p_pipe_aC	0.0849	0.0849	0.0849	0.0849
50	p_CG_truck_aC	0.1019	0.1026	0.1011	0.1052
50	p_LIQ_truck_aC	0.2176	0.2362	0.1893	0.3496
50	p_LOHC_truck_aC	0.3762	0.3609	0.2733	0.4331
50	p_NH3_truck_aC	0.3606	0.3615	0.3531	0.3728
50	p_pipe_aC	0.0849	0.0849	0.0849	0.0849
100	p_CG_truck_aC	0.1067	0.1083	0.1052	0.1135
100	p_LIQ_truck_aC	0.2191	0.2373	0.1906	0.3511
100	p_LOHC_truck_aC	0.3792	0.364	0.2759	0.4367
100	p_NH3_truck_aC	0.3626	0.3637	0.3552	0.3751
100	p_pipe_aC	0.0849	0.0849	0.0849	0.0849
500	p_CG_truck_aC	0.1456	0.1533	0.1381	0.1793
500	p_LIQ_truck_aC	0.2331	0.2482	0.2004	0.3634
500	p_LOHC_truck_aC	0.4035	0.3888	0.2973	0.4652
500	p_NH3_truck_aC	0.3802	0.3815	0.3716	0.3936
500	p_pipe_aC	0.1015	0.1015	0.1015	0.1015
1000	p_CG_truck_aC	0.1942	0.2096	0.1793	0.2616
1000	p_LIQ_truck_aC	0.2455	0.2615	0.2128	0.3788
1000	p_LOHC_truck_aC	0.4339	0.42	0.3241	0.5008
1000	p_NH3_truck_aC	0.4033	0.4038	0.3922	0.4167
1000	p_pipe_aC	0.135	0.135	0.135	0.135
5000	p_CG_truck_aC	0.5832	0.6598	0.5084	0.9197
5000	p_LIQ_truck_aC	0.3533	0.3714	0.3151	0.5066
5000	p_LOHC_truck_aC	0.6727	0.6675	0.538	0.786
5000	p_NH3_truck_aC	0.5836	0.5818	0.5567	0.6016
5000	p_pipe_aC	0.4152	0.4152	0.4152	0.4152

Table 23: Result summary for Sea: Final costs for generation, conversion, transport (FinCost60)

Q	identifier	median	mean	min	max
365	p_LIQ_ship_aC	178.6723	191.5046	75.4004	516.2014
365	p_LOHC_ship_aC	177.0399	187.8941	126.9183	275.2521
365	p_NH3_ship_aC	672.869	822.3304	257.6019	3434.7278
1000	p_LIQ_ship_aC	153.1358	161.8712	74.8263	412.8168
1000	p_LOHC_ship_aC	170.327	181.8484	123.7334	264.6297
1000	p_NH3_ship_aC	511.2603	614.9085	211.3871	2474.5138
5000	p_LIQ_ship_aC	125.0667	131.1051	74.0599	316.6737
5000	p_LOHC_ship_aC	182.366	176.2909	120.1335	254.689
5000	p_NH3_ship_aC	341.7771	402.0825	163.6272	1483.6305
10000	p_LIQ_ship_aC	117.3035	122.3751	73.8637	287.2521
10000	p_LOHC_ship_aC	180.53	174.4522	119.0376	251.5748
10000	p_NH3_ship_aC	291.4759	339.7187	149.9428	1198.2104
100000	p_LIQ_ship_aC	100.2091	104.4354	73.4742	227.2533
100000	p_LOHC_ship_aC	175.982	171.0583	116.9727	247.2023
100000	p_NH3_ship_aC	190.8603	214.3833	121.848	615.7991
180000	p_LIQ_ship_aC	97.6446	101.7917	73.4138	219.0216
180000	p_LOHC_ship_aC	159.3325	170.2352	116.6787	246.5608
180000	p_NH3_ship_aC	176.1503	195.2431	117.5938	526.2705

Table 24: Result summary for Sea: total conversion and transport energy (ConvTransE) per medium with conversion

distance	identifier	median	mean	min	max
100	p_LIQ_ship_aC	0.2235	0.2419	0.1902	0.3706
100	p_LOHC_ship_aC	0.398	0.3869	0.2871	0.4897
100	p_NH3_ship_aC	0.3782	0.3789	0.363	0.3962
200	p_LIQ_ship_aC	0.2244	0.2448	0.191	0.3791
200	p_LOHC_ship_aC	0.401	0.39	0.2889	0.4962
200	p_NH3_ship_aC	0.381	0.381	0.3642	0.399
500	p_LIQ_ship_aC	0.2274	0.2531	0.1933	0.4046
500	p_LOHC_ship_aC	0.4088	0.3993	0.2941	0.5156
500	p_NH3_ship_aC	0.3879	0.3871	0.3679	0.4074
1000	p_LIQ_ship_aC	0.2312	0.2669	0.1973	0.4473
1000	p_LOHC_ship_aC	0.4195	0.4146	0.3027	0.5481
1000	p_NH3_ship_aC	0.3987	0.3974	0.3742	0.4213
5000	p_LIQ_ship_aC	0.2676	0.3777	0.2293	0.7933
5000	p_LOHC_ship_aC	0.5112	0.5385	0.3719	0.8077
5000	p_NH3_ship_aC	0.4704	0.4798	0.4239	0.5324
10000	p_LIQ_ship_aC	0.3142	0.5222	0.2703	1.2372
10000	p_LOHC_ship_aC	0.6173	0.6934	0.4583	1.1323
10000	p_NH3_ship_aC	0.565	0.5826	0.486	0.6713

Table 25: Result summary for Combined Pathways: Final costs per medium for generation, conversion, transport(FinCost60)

distanceonland	identifier	median	mean	min	max
10	p_LIQ_ship_LIQ_truck_aC	122.5262	137.1784	75.3035	470.0529
10	p_LIQ_ship_pipe_aC	131.0757	145.7782	81.075	519.5638
10	p_LOHC_ship_pipe_aC	187.6597	187.5625	124.8148	286.7489
50	p_LIQ_ship_LIQ_truck_aC	123.5176	137.9313	75.4124	469.7602
50	p_LIQ_ship_pipe_aC	130.9279	145.3256	81.3597	523.7366
50	p_LOHC_ship_pipe_aC	188.9099	188.9125	124.4421	294.9782
100	p_LIQ_ship_LIQ_truck_aC	124.2247	138.8821	76.2107	471.8694
100	p_LIQ_ship_pipe_aC	135.4467	149.7481	81.1817	526.4677
100	p_LOHC_ship_pipe_aC	189.0216	190.7146	124.8489	297.7888
500	p_LIQ_ship_LIQ_truck_aC	131.6081	146.134	80.1863	480.4637
500	p_LIQ_ship_pipe_aC	148.624	163.9538	83.0417	645.8579
500	p_LOHC_ship_pipe_aC	196.6382	203.0365	125.8736	395.4806
1000	p_LIQ_ship_LIQ_truck_aC	140.6435	155.2802	84.9738	496.6399
1000	p_LIQ_ship_pipe_aC	162.6327	179.3527	85.8946	673.2846
1000	p_LOHC_ship_pipe_aC	210.2082	219.2529	129.0084	538.7894
5000	p_LIQ_ship_LIQ_truck_aC	218.9498	231.7261	118.9585	601.743
5000	p_LIQ_ship_pipe_aC	271.546	330.8659	110.8299	1849.8203
5000	p_LOHC_ship_pipe_aC	305.1605	374.2564	152.8745	1677.6818

Table 26: Result summary for Combined Pathways: conversion and transport energy (ConvTransE)

distanceonland	identifier	median	mean	min	max
10	p_LIQ_ship_LIQ_truck_aC	0.2574	0.3212	0.1904	1.2375
10	p_LIQ_ship_pipe_aC	0.3408	0.4015	0.2751	1.3221
10	p_LOHC_ship_pipe_aC	0.5152	0.5552	0.372	1.2172
50	p_LIQ_ship_LIQ_truck_aC	0.2584	0.3223	0.1914	1.2387
50	p_LIQ_ship_pipe_aC	0.3413	0.4013	0.2751	1.3221
50	p_LOHC_ship_pipe_aC	0.5153	0.5567	0.372	1.2172
100	p_LIQ_ship_LIQ_truck_aC	0.2595	0.3245	0.1926	1.2402
100	p_LIQ_ship_pipe_aC	0.3413	0.4024	0.2751	1.3221
100	p_LOHC_ship_pipe_aC	0.5152	0.5565	0.372	1.2172
500	p_LIQ_ship_LIQ_truck_aC	0.2704	0.3343	0.2025	1.2525
500	p_LIQ_ship_pipe_aC	0.3579	0.4199	0.2917	1.3387
500	p_LOHC_ship_pipe_aC	0.5318	0.5732	0.3887	1.2338
1000	p_LIQ_ship_LIQ_truck_aC	0.2834	0.3469	0.2149	1.2679
1000	p_LIQ_ship_pipe_aC	0.3909	0.4521	0.3252	1.3721
1000	p_LOHC_ship_pipe_aC	0.5646	0.6054	0.4221	1.2673
5000	p_LIQ_ship_LIQ_truck_aC	0.3944	0.4568	0.3172	1.3957
5000	p_LIQ_ship_pipe_aC	0.6716	0.7324	0.6054	1.6523
5000	p_LOHC_ship_pipe_aC	0.8454	0.8861	0.7023	1.5475